Risk Assessment Guidelines

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List of Acronyms

NBS = Nature Based Solutions

EWS = Early Warning Systems

PIISA = Piloting Innovative Insurance Solutions for Adaptation

EP = Exceedance Probability

EAD = Expected Annual Damage

RCP = Representative Concentration Pathway

SSP = Shared Socioeconomic Pathway

HIP = Hazard Information Profiles

IPCC = Intergovernmental Panel of Climate Change

NOAA = National Oceanic and Atmospheric Administration

FEMA = Federal Emergency Management Agency

UNDRR = United Nations Office for Disaster Risk Reduction

AR = Assessment Report

GLM = Generalized Linear Modelling

DTM = Digital Terrain Models

DEM = Digital Elevation Models

DSM = Digital Surface Models

TI = Temporal Indices

TAI = Total Adjustment Index

CMIP = Coupled Model Intercomparison Project

ESM = Earth System Models

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RCM = Regional Climate Models

GCM = Global Climate Models

EBA = Ecosystem Based Adaptation

Eco-DRR = Ecosystem-based Disaster Risk Reduction

GI = Green Infrastructure

WSUD = Water Sensitive Urban Plans

HMP = Hazard Mitigation Plans

PPP = Public-Private Partnership

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Glossary

- **Actuarial Models**: Statistical models that estimate risk using empirical loss data from past events, commonly used by insurance companies.
- **Adaptation**: Actions taken to adjust to actual or expected climate effects to reduce harm or exploit beneficial opportunities.
- **Catastrophe Models**: Complex computer simulations that combine hazard, exposure and vulnerability data to estimate potential losses from natural disasters.
- **Climate Change**: Long-term shifts in global weather patterns and average temperatures caused by human activities and natural factors.
- **Damage Curves**: Functions that relate hazard intensity (e.g., flood depth) to expected economic damage for specific assets or land uses.
- **Early Warning Systems (EWS):** Frameworks that integrate hazard monitoring, forecasting, risk assessment and preparedness activities to enable pre-emptive action.
- **Expected Annual Damage (EAD)**: The anticipated average yearly economic loss from hazards, calculated by combining damage estimates across different probability scenarios.
- **Exposure**: The presence of people, assets, systems, or other elements in hazard zones that could be adversely affected.
- **Global Climate Models (GCM)**: Computer models that simulate Earth's climate system at a global scale.
- **Hazard**: A dangerous phenomenon, substance, human activity, or condition that may cause loss of life, injury, property damage and other impacts.
- **Nature-Based Solutions (NBS)**: Actions to protect, sustainably manage and restore ecosystems to address societal challenges while providing human wellbeing and biodiversity benefits.
- **Regional Climate Models (RCM)**: Higher-resolution climate models that focus on specific geographic regions.
- **Representative Concentration Pathways (RCP)**: Scenarios that describe different possible future greenhouse gas concentration trajectories.
- **Resilience**: The ability of systems to cope with hazardous events by responding and reorganizing while maintaining essential functions.
- **Risk Assessment**: The process of evaluating potential adverse consequences by analyzing hazards,

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exposure, and vulnerabilities.

- **Shared Socioeconomic Pathways (SSP)**: Scenarios that describe alternative futures of societal development that would make climate mitigation and adaptation challenging.
- **Vulnerability**: The characteristics that make systems susceptible to damaging effects of hazards, including sensitivity and lack of adaptive capacity.

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1. Introduction

This report has been developed as part of the SOTERIA project. The main goal of SOTERIA is to explore and implement innovative adaptation mechanisms, specifically insurance-based solutions, to tackle the growing risks associated with climate change. This document focuses specifically on developing guidelines for climate-related risk assessment to aid adaptation planning and implementation at local, regional, and national levels.

The main goal is to provide a comprehensive, evidence-based framework for evaluating climate risks. It begins with a diagnosis of existing scientific approaches, methods, and tools for risk assessment, including a detailed literature review that synthesizes the current understanding of hazards, exposure, and vulnerability. This foundational research identifies both strengths and gaps in current methodologies, drawing insights from academic research and expert interviews within the insurance sector.

Building on this diagnostic, these guidelines outline a robust risk assessment framework that integrates an understanding of established methodologies with practices from the insurance sector. Also, the role of climate change is detailed, emphasizing the importance of forward-looking models and scenarios to project future impacts. Concluded by exploring critical adaptation measures, including Nature-Based Solutions (NBS) and Early Warning Systems (EWS), highlighting their significance in enhancing resilience and reducing climate-related damages.

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2. Risk assessment diagnosis

2.1 Diagnosis of methods and tools for risk assessment

2.1.1 Literature review

The purpose of this section is to identify, analyse, and synthesise existing scientific approaches, methods, and tools used in climate-related risk assessment. The aim is to inform the development of a structured and evidence-based framework that enables regions to characterise and quantify climate risks, based on hazard, exposure, and vulnerability dimensions.

The methodology applied in this review is based and beyond on the approach used in the **PIISA Project, (2024)** https://piisa-project.eu/, specifically its **Deliverable D1.2 Advancements in Actuarial Risk Modelling.** Although the PIISA report covers both risk and insurance modelling, only the risk assessment component has been considered relevant for the scope of this document. Accordingly, the methods applied for literature identification, selection, and analysis were adapted to focus exclusively on risk-related content.

2.1.1.1 Keywords and Dataset Querying

The search was conducted using the Scopus database, targeting peer-reviewed journal articles published in English. The search was restricted to article titles, abstracts, and keywords, ensuring thematic relevance. The resulting initial dataset comprised 449, representing a broad spectrum of climate-related risk assessment literature across various hazard types and methodological approaches.

The keywords used are: climate-related risk; hazard; exposure; vulnerability; climate adaptation; catastrophe modelling; probabilistic modelling; multi-hazard assessment; spatial risk analysis; insurance-linked risk assessment; risk governance; climate change projections; nature-based solutions; early warning systems; damage curves; expected annual damage.

2.1.1.2 Screening

The screening process was conducted using the Assisted tool Rayyan, enabling a systematic review and

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transparent documentation of inclusion/exclusion decisions. Only articles dealing explicitly with risk assessment methodologies were retained.

After applying these criteria, a total of 449 articles were selected for full review. These publications cover a range of risk assessment frameworks, including catastrophe models, probabilistic and scenario-based approaches, as well as spatially explicit models integrating hazard, exposure, and vulnerability data.

A thorough screening of these **449 articles** was subsequently carried out to refine the selection and ensure relevance and applicability to the objectives of the SOTERIA project. This process involved multiple rounds of assessment based on methodological robustness, clarity of application, and alignment with the project's focus areas.

A total of 62 articles were reviewed under the SOTERIA screening, comprising: 18 articles selected through the SOTERIA screening process itself, 33 references from the bibliography of Deliverable D1.2 Advancements in Actuarial Risk Modelling (Michiel et al., 2024), and 11 references from the bibliography of Deliverable D1.3 Design and Modelling Framework for WP3 Pilots (Kaploun et al., 2024). All PIISA deliverables are available at the project website: https://piisa-project.eu/.

Together, these articles cover a wide range of geographic contexts, from global-scale models to highly localised case studies. The geographic distribution is far from uniform and reflects the availability of hazard and loss data, the maturity of modelling approaches, and the economic relevance of certain risks.

2.1.1.3 Discussion

The review of 18 selected articles reveals five main categories of climate risk assessment models: Catastrophe Models, Actuarial Models, Conceptual Models, Dynamic Decision Models, and Global Single-Hazard Models. The following sections describe each type, highlighting their geographical application, scenario integration, adaptation considerations, vulnerability representation, and approach to risk estimation.

2.1.1.3.1 Risk model types

Based on the full set of scientific literature obtained through the SOTERIA screening process, it has been possible to identify and classify the main types of models used for climate-related risk assessment.

Figure 1 presents the quantitative distribution of the identified model types across the reviewed sample,

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highlighting the dominance of catastrophe and actuarial approaches, and the emerging role of technology-enabled and simulation-based modelling in climate risk assessment.

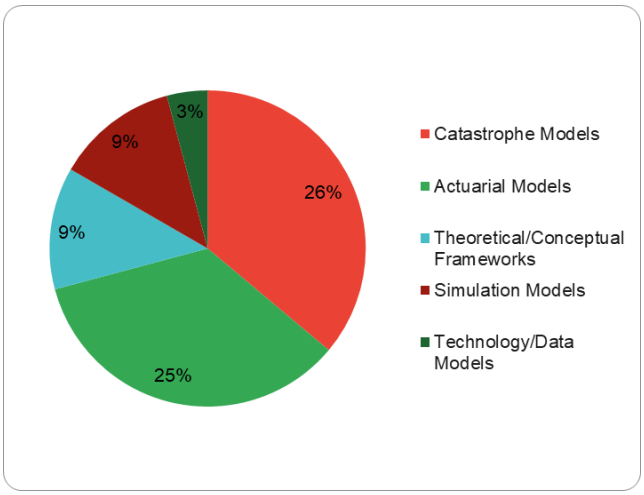

Figure 1. Quantitative distribution of the identified model types

Catastrophe models

In catastrophe modelling, climate risk is simulated by combining quantitative information on hazard impacts and associated occurrence probabilities with data on exposed elements at risk and their vulnerability. This multi-layered approach allows for the construction of exceedance probability (EP) curves, which illustrate the likelihood of losses surpassing specific thresholds, and the estimation of Expected Annual Damage (EAD).

Several studies from the SOTERIA literature screening adopt catastrophe modelling due to the high-impact, low-frequency nature of hazards such as flooding, hurricanes, and wildfires, which limits the availability of reliable historical loss data. For example (Tesselaar et al., 2020), employ a probabilistic flood risk model for Europe that integrates hazard footprints, exposure datasets, and depth–damage curves to quantify EAD under current and future climate scenarios. Similarly (De Ruig et al., 2022), economic flood losses in Western Europe using a stochastic simulation framework linked to Representative Concentration Pathway (RCP) climate projections. In the hurricane domain, Peng et al. (2014) simulate coastal storm surge risk by coupling hazard intensity distributions with infrastructure vulnerability functions.

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Other applications extend catastrophe modelling to multi-hazard contexts. For instance, (Ermolieva et al., 2017) develop a probabilistic modelling platform capable of capturing cascading effects between hazards, while (Perazzini et al., 202pe4) apply a spatially explicit framework to evaluate flood risk mitigation strategies in Italy under climate change scenarios. In wildfire risk assessment, Boudreault et al. (2020) integrate fire spread simulations with economic exposure layers to estimate both direct and indirect losses.

One advantage of catastrophe modelling is its flexibility to incorporate future climatic and socio-economic conditions—including alternative RCPs and Shared Socioeconomic Pathways (SSPs), making it particularly relevant for climate adaptation planning. Moreover, risk outputs can be mapped spatially, enabling decision-makers to visualize losses per pixel or per administrative unit, which supports localized policy interventions.

However, catastrophe models are computationally demanding and require extensive hazard probability, exposure, and vulnerability datasets. Their accuracy is sensitive to the quality and resolution of input data, which can be a limiting factor in regions with sparse observational records.

Actuarial models

Actuarial models estimate risk using empirical loss data from past events, in contrast to catastrophe models, which rely on hazard simulations. These models apply statistical and econometric techniques, such as regression analysis, time series modelling, or bootstrapping to quantify the relationship between hazard occurrence, exposure, and observed damages.

Within the SOTERIA literature screening, actuarial approaches are often applied where hazard data are frequent and well-recorded, allowing loss trends to be inferred from historical events. For example, (Barreal et al., 2014) develop an actuarial wildfire risk model for Spain, using regression analysis to link annual burned area to socio-economic, geographic, and climate-related predictors. Pinheiro and Ribeiro (2013) estimate wildfire risk in Portugal by modelling the expected annual burned area per municipality, based on historical fire occurrence data.

In the windstorm domain, (El-Adaway et al., 2012) combines actuarial methods with bootstrapping techniques to enhance the statistical robustness of wind loss estimates, generating simulated datasets from a limited number of observed storm events. In agricultural insurance, (Hu et al., 2024) apply index-based actuarial models to estimate drought and flood risk for smallholder farmers in India, using historical yield loss records to price microinsurance products.

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A key advantage of actuarial models is their transparency and interpretability for both practitioners and regulators. They are particularly useful when physical hazard models are unavailable or when historical data capture loss-generating processes not yet fully understood from a physical science perspective.

However, actuarial models face significant limitations when dealing with high-impact, low-probability hazards, such as extreme floods or major hurricanes, where loss data are scarce. This limitation constrains their predictive capacity in the context of non-stationary climate risks, where hazard frequency and severity are changing over time.

Theoretical – Conceptual models

Theoretical or conceptual models represent risk through qualitative or abstract frameworks rather than direct empirical or simulated loss data. These models define risk as a function of hazard, exposure, and vulnerability, but do not estimate losses through a numerical risk engine. Instead, they serve to structure the understanding of climate risks and guide decision-making, often in policy and strategic planning contexts.

Theoretical models are used to standardize hazard definitions and classify risk elements across multiple disciplines and governance levels. For example, the UNDRR/ISC Hazard Definition and Classification Review (2020) establishes a common taxonomy of 302 hazards across eight thematic clusters, providing Hazard Information Profiles (HIPs) to support national risk assessment and reporting processes. Similarly, the Sendai Framework for Disaster Risk Reduction 2015–2030 offers a governance-focused conceptual approach, emphasizing risk prevention, preparedness, and resilience-building across all hazard types.

Other conceptual frameworks from the reviewed studies are designed to integrate multi-hazard contexts into climate adaptation planning. The ICARIA Holistic Modelling Framework (2023) links hazard occurrence to exposure and vulnerability through “elementary bricks” that represent interconnected climate hazards (heatwaves, floods, wildfires, droughts, storms), allowing for the consideration of cascading effects. These frameworks are particularly relevant for regions lacking detailed hazard or loss datasets, enabling high-level risk prioritization while aligning with the IPCC AR6 risk concept.

Simulation models

Technology/data models focus on the integration of advanced data sources and computational techniques to improve the spatial and temporal resolution of risk assessments. Examples include the use of remote sensing for exposure mapping, machine learning for hazard footprint prediction, and geospatial platforms

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for near real-time hazard monitoring ((Hu et al., 2024); (Perazzini et al., 2024)). These models are particularly valuable in data-scarce environments, as they can supplement traditional hazard and vulnerability datasets.

Technology / Data models

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2.1.1.3.2 Hazard types

The literature review conducted for the SOTERIA project identified a range of climate-related hazards modelled in the selected studies. Following the IPCC AR6 hazard categories and the classification used in the screening process, the hazards fall into four main groups: floods, hurricanes/tropical cyclones, wildfires, and droughts.

Figure 2 presents the quantitative distribution of the identified hazard types across the reviewed sample.

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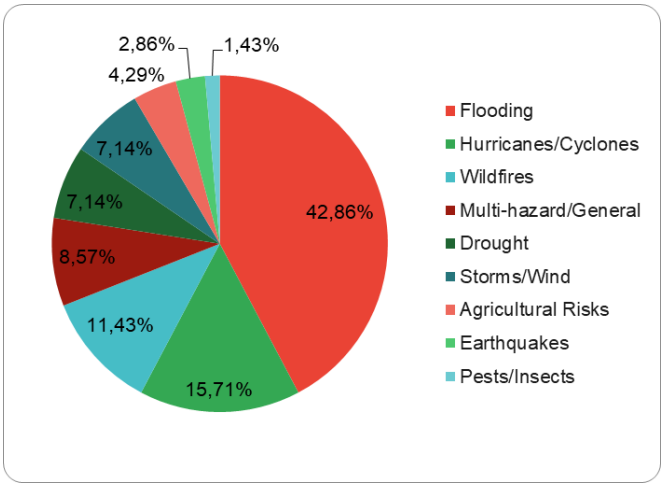

Figure 2. Quantitative distribution of hazard types

Floods

Flood-related hazards are the most frequently addressed, appearing in 42,86% of the reviewed studies. They include fluvial floods, pluvial floods, and coastal floods (storm surge and sea-level rise impacts). Many catastrophe models simulate flood hazard footprints (extent, depth, duration) combined with exposure and vulnerability data to EAD (e.g., (Tesselaar et al., 2020); (De Ruig et al., 2022)). Coastal flooding is often modelled in combination with tropical cyclones, while inland flooding studies use hydrological and hydraulic models to simulate hazard scenarios. The prominence of floods in the literature reflects both their global economic impact and the availability of hydrological datasets for modelling.

Hurricanes / Tropical Cyclones

Hurricanes and tropical cyclones account for 15,71% of the reviewed studies. These hazards are typically high-impact, low-frequency events and are often addressed through probabilistic catastrophe modelling to account for the uncertainty in track, intensity, and landfall location (e.g., (Peng et al., 2014); (Gray, 2021)). In some cases, hurricane modelling is combined with storm surge simulations to capture compound coastal flooding impacts. The integration of climate change scenarios (RCPs/SSPs) in these models allows for assessing the potential intensification of wind speeds, storm surge heights, and rainfall rates in a warming climate.

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Wildfire

Wildfires appear in 11,43% of the reviewed studies, reflecting both their increasing occurrence under climate change and their substantial socio-economic impacts. Actuarial models are frequently used in this domain when sufficient historical burned-area data are available (Pinheiro & Ribeiro, 2013). Other studies use spatial simulation of fire spread combined with exposure datasets to estimate direct and indirect losses (Boudreault et al., 2020). Wildfire risk modelling often includes socio-economic vulnerability indicators, such as population density, land use patterns, and suppression capacity.

Droughts

Drought hazards are present in **7,14%** of the reviewed studies, often linked to **agricultural insurance applications** in emerging markets. Models typically use historical yield loss data and climatic indices (e.g., Standardized Precipitation Index, soil moisture anomalies) to price index-based insurance products. While droughts are a slower-onset hazard compared to floods or hurricanes, their modelling poses challenges due to the multi-dimensional nature of drought impacts (agriculture, water supply, ecosystems).

- **Agricultural Risks** (4,29%): Beyond drought, some agricultural risk models include pest outbreaks, extreme rainfall, or temperature anomalies, often for the purpose of pricing microinsurance.
- **Pests and insects** (1,43%) are one case addresses pest outbreaks as a climate-sensitive hazard affecting agriculture, using historical occurrence records and environmental suitability models.

Multi-hazard

These studies assess risk across multiple hazards or at a general framework level, often incorporating compound event analysis and cascading impacts ((Ermolieva et al., 2017); ICARIA Project, 2023). Hazards considered include combinations such as floods and droughts, or heatwaves and wildfires, providing an integrated approach to adaptation planning.

Storm/wind

Windstorm hazard models rely on either catastrophe simulations or actuarial analysis of historical wind loss records (El-Adaway et al., 2012). These studies often focus on infrastructure vulnerability and the financial implications for insurance portfolios.

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2.1.1.3.3 Geographic scope

The 62 articles reviewed in the SOTERIA screening, including the 18 papers drawn from the PIISA project references, cover a wide range of geographic contexts, from global-scale models to highly localised case studies. Their geographic distribution is uneven, reflecting differences in the availability of hazard and loss data, the maturity of modelling approaches, and the economic significance of the risks considered.

Figure 3 presents the quantitative distribution of the identified geographic locations across the reviewed sample.

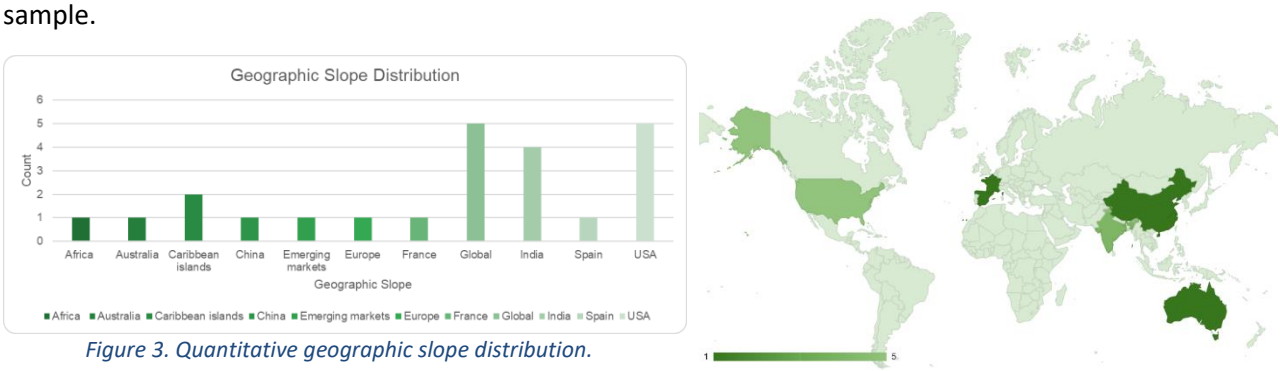

Figure 3. Quantitative geographic slope distribution.

United States of America

A significant share of studies focuses on the US coastal regions—particularly Florida, the Gulf Coast, and the Eastern Seaboard—due to the high exposure to hurricanes, storm surge, and coastal flooding (Peng et al., 2014); (Gray, 2021)). The US context benefits from extensive hazard datasets (e.g., NOAA, FEMA) and a mature catastrophe modelling industry, which facilitates probabilistic modelling and scenario testing. North America also appears in wildfire risk assessments, notably in California (Boudreault et al., 2020), where models integrate fire spread simulations with spatial exposure data.

Western Europe

Western Europe is strongly represented in flood risk studies, especially in the Netherlands, Spain, Austria, and Italy ((Tesselaar et al., 2022); (De Ruig et al., 2023); (Perazzini et al., 2022)). Many of these models adopt an integrated hazard–exposure–vulnerability framework and use high-resolution hydrological and economic datasets. The European Union's policy environment, including the Floods Directive and adaptation strategies, provides a favourable context for climate risk assessment research.

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Mediterranean and Southern Europe

Flood, wildfire and drought risks are frequently studied in Spain, Portugal, and Italy (Pinheiro & Ribeiro, 2013), where Mediterranean climate conditions and vegetation types create high seasonal hazard potential. These studies often combine biophysical hazard modelling with socio-economic vulnerability analysis, highlighting the role of land use and forest management in adaptation.

Asia and the pacific

Asia is present mainly through tropical cyclone and flood models in China, India, and Southeast Asia (Chen et al., 2020). In India, the focus is on agricultural drought and flood risks, often linked to microinsurance applications. These models face greater data scarcity than their US or European counterparts, but they highlight innovative parametric approaches to overcome gaps in historical records.

Africa and the Caribbean

Emerging market contexts in Sub-Saharan Africa and small Caribbean islands appear in studies addressing drought, agricultural losses, and hurricane risk (Joyette et al., 2015). These regions often rely on simplified catastrophe models or actuarial methods due to limited hazard and exposure datasets. The emphasis here is on adaptation through risk transfer—particularly microinsurance and index-based schemes—rather than high-resolution physical modelling.

Global-scale models

Some studies adopt a global hazard scope, particularly in wildfire and multi-hazard contexts (Ermolieva et al., 2017). These models provide harmonised risk maps at coarse resolution, useful for identifying global hotspots but requiring downscaling for local adaptation planning.

2.1.2 Guidelines at the European and national level

To complement the literature review and diagnostic analysis, a selection of key European and international guidelines has been compiled and reviewed. These documents, developed by institutions, research projects, and international frameworks, provide practical approaches, standardized methodologies, and innovative perspectives on climate and disaster risk assessment. Their inclusion in this report serves two main purposes: first, to map the existing landscape of reference tools and frameworks that are currently guiding risk assessment practices; and second, to provide a solid knowledge base for the development of

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the Risk Assessment Guidelines proposed later in this document.

By synthesizing their main contributions, we ensure that the guidelines presented in SOTERIA build on established good practices while addressing identified gaps and advancing towards more integrated, forward-looking, and actionable approaches.

User Guide for the Integrated Risk Analysis Tool for Climate and Disaster Risk

The “User Guide for the Integrated Risk Analysis Tool for Climate and Disaster Risk” was developed by CAF and UNDRR to support local governments in assessing urban risks. It uses a qualitative methodology to analyze threats and vulnerabilities through specific indicators. The tool evaluates both current (baseline) and future risks under climate change scenarios. It includes practical case studies, such as Bella Unión (Uruguay). The guide is designed for municipal staff, civil society, and educational institutions. Though not a substitute for detailed studies, it aids initial and participatory decision-making.

Mapping and Evaluation of the best practices of insurance pircing and innovative insurance solutions

Climate change impacts in Europe demand insurance strategies beyond traditional models. Innovative solutions include index-based insurance, nature-based coverage, and parametric products. The report reviews pricing methods, premium management, and payout structures. Emphasis is placed on climate data use, risk modelling, and digital tools such as blockchain. Examples of supportive IT services and emerging business models are discussed. Public-private partnerships are highlighted to support climate adaptation. Public procurement and financial innovation are also addressed. The overall goal is to strengthen disaster resilience and promote sustainable insurance coverage.

ICARIA

D1 Holistic Modelling Network

The ICARIA modelling framework assesses risks and impacts from multiple climate hazards (e.g., heatwaves, wildfires, droughts, floods, and storms), including compound events and cascading effects. It integrates exposure, vulnerability, resilience capacities, and human behavior to estimate both direct and indirect damages. The model defines "elementary bricks" to structure the analysis and uses climate projections to assess future scenarios. Time and space are key variables, and the framework is tested in case studies in Barcelona, South Aegean, and Salzburg. It incorporates resilience measures as coping, adaptive, and transformative responses. Quantitative metrics are introduced to assess urban resilience.

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The ultimate goal is to support informed and sustainable decisions for adapting critical infrastructure and services to climate change.

D2 Holistic Modeling Framework for Multi-hazard events

Deliverable 2.1 aims to identify current climatic hazards affecting three case study regions (Barcelona Metropolitan Area, Salzburg Region, and South Aegean Region) and analyze their evolution under climate change scenarios. The study analyzes extreme multi-hazard events to understand interaction mechanisms between individual climate hazards, while also documenting historic extreme climate events that have impacted these regions. This work supports developing a comprehensive framework for assessing risks from complex, compound and cascading disasters, focusing on both single and multi-hazard perspectives. The findings will help improve understanding of how different hazards interact and impact critical infrastructure and communities across diverse European regions.

UNDRR/ISC Sendai Hazard Review

A comprehensive international effort to standardize hazard definitions and classifications for disaster risk reduction. Through extensive consultation with over 500 technical experts, developed a detailed list of 302 hazards grouped into eight major clusters: meteorological/hydrological, extraterrestrial, geohazards, environmental, chemical, biological, technological, and societal hazards. Created standardized Hazard Information Profiles (HIPs) for each hazard, sourcing definitions from authoritative sources like UN agencies and scientific bodies. The project aims to support countries in reviewing and strengthening their risk reduction policies and operational practices. Makes six key recommendations including regular review and updates of hazard definitions, developing a multi-hazard information system, and addressing cascading/complex hazards. Promotes international cooperation and standardized approaches to hazard classification. Helps shift understanding from managing disasters as isolated events to managing risks systematically. Provides foundation for enhanced risk reduction strategies and improved loss data collection. Emphasizes need for evidence-based decision making in disaster risk reduction. Recognizes the dynamic nature of hazards and need for regular updates. Supports implementation of the Sendai Framework goals through improved hazard understanding.

Sendai Framework Framework for Disaster Risk Reduction 2015-2030

A landmark agreement adopted at the Third UN World Conference in March 2015 as successor to the Hyogo Framework for Action. Represents a major shift in approach by emphasizing disaster risk management over traditional disaster management. Defines seven specific global targets aimed at

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substantially reducing disaster risks and losses. Promotes state responsibility while encouraging all-of-society engagement and participation. Significantly broadens scope to cover both natural and human-induced hazards, including environmental, technological and biological risks. Articulates need for improved understanding of disaster risk in all dimensions. Emphasizes strengthening disaster risk governance and accountability at all levels. Promotes investment in disaster risk reduction for resilience building. Enhances disaster preparedness for effective response. Strengthens international cooperation and global partnerships. Recognizes special needs and circumstances of developing countries. Promotes coherence across policies, plans and programs. Encourages risk-informed public and private investments. Emphasizes importance of building back better in recovery phase.

Hazard Definition Classification Review

Establishes a systematic two-step process for reviewing and validating hazard definitions and classifications. First evaluates draft hazard list for comprehensiveness and coherence through broad consultation. Then conducts detailed review of inclusion/exclusion criteria, final hazard list, and individual Hazard Information Profiles. Ensures hazard definitions are scientifically robust and reflect broad expert consensus. Requires reviewers to evaluate if definitions align with scientific understanding and fit within UN General Assembly hazard framework. Provides detailed guidance for authors and reviewers of hazard profiles to ensure consistency. Emphasizes importance of sourcing definitions from highest scientific authorities and UN agencies. Involves extensive consultation with scientific experts across disciplines. Builds consensus through systematic review and feedback process. Promotes standardization while allowing for evolving understanding of hazards. Considers both technical accuracy and accessibility to non-technical audiences. Establishes clear criteria for hazard inclusion and classification. Creates foundation for improved hazard monitoring and reporting. Supports evidence-based disaster risk reduction policies and practices. Facilitates international cooperation through common understanding of hazards.

The concept of risk in the IPCC Sixth Assessment Report

Risk in the IPCC AR6 Report represents a comprehensive framework for understanding potential adverse consequences in climate change contexts. At its core, it encompasses both direct climate impacts and responses to climate change, operating through complex interactions of hazards, exposure, and vulnerability. The framework explicitly acknowledges uncertainty and incomplete knowledge as fundamental components, requiring careful characterization of magnitude, reversibility, and distributional effects. For climate impacts, risk emerges from the dynamic interplay between climate-related hazards and the vulnerability of affected systems, while for climate responses, risk stems from potential failures of

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intended actions or unintended negative side-effects on societal objectives. The concept deliberately focuses only on adverse outcomes, distinguishing it from opportunities or benefits, and demands rigorous assessment of uncertainties and confidence levels. This sophisticated understanding goes beyond simple probability calculations, incorporating socio-economic changes, human decision-making, and complex system interactions. The framework serves as a crucial tool for decision-makers, enabling them to evaluate, compare, and manage potential adverse consequences across different scenarios and response options, ultimately supporting more informed and effective climate action strategies.

2.1.3 Interviews with the insurance sector

Researchers conducted interviews with associated partners in the insurance sector across multiple case studies to examine approaches to risk assessment and their influence on premium calculations. The findings offer detailed insights into the methodologies and practices insurance companies use to evaluate risks and establish pricing strategies. The interviews clarify the specific factors and parameters included in risk assessment frameworks and their direct effects on premium determination.

Table 1. Summary of interviews with insurance's associated partners.

Case Study	Partner	Risk data	Key Findings and Risk Assessment Analysis
Valencia	CSS	Collaboration with National Water Agency (DGA)	● Public insurance agency responsible for natural catastrophe in Spain. ● In collaboration with the National Water Agency, National Meteorological Agency, and other institutions, they established data-sharing partnerships to compile and analyse loss-related information, creating damage curves. ● They don't develop internal hazard or risk models.
Gabrovo	DZI at KBC	Impact Forecast. AON Benfield	● Risk-based pricing methodology employs variable approaches contingent upon data availability and quality metrics. ● **Historical Claims Analysis:** ○ Utilizes Burning Cost Analysis for loss experience evaluation. ○ Implements Generalized Linear Modelling (GLM) where comprehensive data exists.

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			• **Advanced Risk Assessment:**
			  ○ Employs sophisticated Impact Forecasting methodologies.
			  ○ Kat Risk (AON Benfield) identified as premier flood risk assessment tool for 2023.
			  ○ Utilizes median values at 1/200 return period for risk calculations.
			• **Regulatory Compliance:**
			  ○ Impact forecasting models guide reinsurance capacity allocation.
			  ○ Ensures adherence to Solvency 2 Natural Catastrophe scenario requirements.
			  ○ Maintains safeguards against potential capital threshold breaches.

Trondelag	KLP	Historical claims. Starting work with seven analytics	• **Coverage Parameters:**
			  ○ Includes stormwater and rainwater events.
			  ○ Focuses on fluvial flooding, with noted complexity in distinguishing between fluvial and pluvial boundaries.
			• **Pricing Structure:**
			  ○ Implements flat rate system.
			  ○ Adheres to Norwegian natural catastrophe pool regulations.
			• **Risk Assessment Methodology:**
			  ○ Current reliance on historical data analysis
			  ○ In transition phase to implement seven analytics platforms
			  ○ EAD calculations pending implementation.
			• **Technical Limitations:**
			  ○ Absence of damage curve utilization.
			  ○ Lack of institutional partnerships for damage curve development.
			• **Policy Structure:**
			  ○ Annual contract basis.

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			○ Climate change considerations integrated via multiplier factor. ● **Risk Mitigation Approach:** ○ Limited to Knowledge Bank information dissemination. ○ Minimal adaptation incentive programs due to low customer retention. ● **Development Requirements:** ○ Enhanced support needed for local and regional authorities. ○ Improved utilization of Knowledge Bank risk data for measure implementation.
	GJE	Created by his own with National Computacional Center with precipitation	● Coverage scope encompasses stormwater and rainwater, focusing on fluvial flooding (with noted complexity in boundary definition between fluvial and pluvial flooding). ● Premium structure follows flat-rate methodology, aligned with Norwegian regulatory framework for natural catastrophe pool. ● **Risk Assessment Framework:** ○ Currently relies on historical data analysis. ○ Transitioning to incorporate seven analytics platforms. ○ EAD calculations not yet implemented. ● **Damage assessment limitations:** ○ Absence of damage curve implementation. ○ No active institutional collaborations for damage curve development. ● **Contract Structure:** ○ Annual renewal basis. ○ Climate change factor incorporated through multiplication coefficient. ● **Adaptation Strategy:** ○ Limited to Knowledge Bank information sharing. ○ Minimal customer-focused adaptation incentives due to low retention rates.

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			● **Strategic Need:** ○ Enhanced support required for municipal and regional authorities in measure implementation, leveraging Knowledge Bank risk data.
Bavaria	AZA	They ara starting to elaborate some models. Usa CatNat models provided by Allianz RE	● **Natural Catastrophe Coverage:** ○ Primary perils: Hail, frost, torrential rain, and drought. ○ Drought coverage structured through parametric precipitation-based models. ○ Flood coverage not included in market offerings. ● **Market Structure and Pricing:** ○ Operates within free market parameters. ○ Premium calculation primarily based on historical loss data. ○ Progressive implementation of modelling approaches in select regions. ○ Utilizes models from Allianz RE and external providers (Catrisk). ● **Contract Structure:** ○ Flexible terms ranging from 1 to 5 years. ○ Drought coverage limited to annual contracts due to risk factors. ● **Risk Assessment Limitations:** ○ Absence of damage curve collaboration with administrative bodies. ○ Complex hazard parameter interactions impede development. ● **Data Sharing Framework:** ○ Loss data shared through German Insurance Association. ○ Anonymous data dissemination to public administration at municipal level. ● **Strategic Gaps:** ○ No current climate change scenario analysis.

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			○ Absence of adaptation measure enhancement initiatives.

The analysis of insurance sector interviews reveals a complex landscape of natural catastrophe coverage and risk assessment approaches across different entities. Several key patterns emerge: First, there's a notable variation in technological sophistication and data utilization, with some organizations employing advanced risk assessment tools like Impact Forecasting and Kat Risk, while others, most of them, still heavily rely on historical data analysis. Most insurers are in transition towards more sophisticated analytics platforms, though many faces strong limitations in damage curve implementation and institutional partnerships.

Second, there's a consistent challenge across the sector regarding climate change integration and adaptation strategies. While some entities incorporate climate factors through multipliers or coefficients, there's a general lack of comprehensive climate change scenario analysis and adaptation measure enhancement initiatives. The industry appears to be struggling with risk assessment sophistication, and practical implementation of adaptation measures, particularly given challenges like low customer retention rates and complex hazard parameter interactions. Data sharing and collaboration with public institutions emerge as critical factors for future development, though current implementation varies significantly across organizations.

2.2 Best practices and gaps in risk assessment

The comprehensive evaluation of methods and tools reveals a landscape marked by best practices and significant gaps. Among the best practices, the widespread adoption of the IPCC's risk assessment framework stands out as a foundational strength. Current methodologies often incorporate a variety of modeling approaches. These range from computationally intensive catastrophe models, which simulate impacts and probabilities for high-impact, low-frequency events, to actuarial models based on empirical data for well-documented hazards, and theoretical-conceptual models that qualitatively structure risk understanding. There is also an increasing recognition of the need for multi-hazard approaches that consider complex interactions and cascading effects, moving beyond isolated single-hazard analyses. Furthermore, integrating forward-looking climate change scenarios, such as SSPs, into models—particularly catastrophe models—is crucial for effective adaptation planning. Efforts by organizations like

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UNDRR and the Sendai Framework to standardize hazard definitions and promote comprehensive governance are significant advancements.

Despite these advancements, several major gaps and challenges hinder the development of a fully robust and actionable climate risk assessment. A primary issue is data scarcity and quality, especially concerning historical loss data related to high-impact, low-probability hazards, which restricts the predictive capacity of actuarial models. Additionally, there is often a lack of spatially explicit hazard values for individual events, and pluvial flood maps are rarely available, even though they have a significant impact.

While advanced catastrophe models are powerful tools, they require extensive and high-resolution datasets that are not consistently available, particularly in data-scarce environments like emerging markets. Alarmingly, fewer than half of existing studies on climate risk insurance fully incorporate future climate change scenarios, and even fewer consider socioeconomic development scenarios, indicating a substantial gap in forward-looking predictive analysis. The inherent uncertainties arising from model assumptions, data limitations, and expert judgment also need to be carefully managed to ensure the reliability of assessments.

The insurance sector faces specific challenges that contribute to these gaps. Many insurers primarily rely on historical data analysis and generally lack comprehensive climate change scenario analysis and initiatives to enhance adaptation measures. There are limitations in integrating advanced tools, such as damage curves, and insufficient institutional partnerships for their development. Additionally, issues like low customer retention rates can impede the implementation of adaptation incentive programs, and complex interactions between hazard parameters complicate sophisticated risk assessments.

These findings underscore an urgent need for enhanced data sharing, improved modeling sophistication, and stronger collaboration between public administrations and the insurance sector. Bridging these critical gaps is essential to advance effective climate adaptation strategies collectively.

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3. Risk Assessment Framework

3.1 General Framework

Building upon the comprehensive analysis of current risk assessment methodologies and insurance sector practices, this framework represents a critical evolution in how municipalities, regions, and insurance companies approach climate-related risk evaluation. The European Environment Agency (European Environment Agency, 2019) emphasizes that traditional risk assessment models are increasingly inadequate for capturing the complex, interconnected nature of climate risks, particularly as extreme weather events become more frequent and severe. The framework's multi-scenario approach enables stakeholders to evaluate risks under various SSPs, providing a more robust foundation for decision-making.

The implementation of this reference framework addresses a fundamental challenge identified by the IPCC, 2023: the need for actionable risk information that bridges the gap between climate science and practical adaptation planning. By incorporating both current conditions and future projections, the methodology enables to prioritize key infrastructure investments and zoning decisions, while providing insurance companies with the granular data necessary for accurate pricing and product development, ensuring business long-term viability. Therefore, collaboration between the public administration and the insurance sector is key to developing the methodology presented in these guidelines.

The IPCC risk assessment framework has been widely adopted in research initiatives evaluating climate-related risks and resilience. The IPCC's Fifth Assessment Report (AR5) introduced a risk-based approach, representing a significant shift from the vulnerability-focused frameworks of previous assessments (IPCC, 2014). This approach integrates established principles from risk sciences and emergency management, which have demonstrated effectiveness in addressing geophysical hazards such as earthquakes, volcanic eruptions, and tsunamis (UN-DHA, 1993; UNDRO, 1980). By combining these methodologies with recent advances in earth and environmental sciences, the IPCC has facilitated greater collaboration between the Disaster Risk and Climate Change research communities. This integration supports a more comprehensive understanding of climate-related risks and their impacts (Connelly et al., 2018).

Three core components form the foundation of the IPCC's risk assessment framework: hazard, exposure and vulnerability (IPCC, 2014). Climate-related physical events or trends constitute hazards, encompassing extreme weather phenomena, sea-level rise, and long-term shifts in temperature and precipitation

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patterns. The presence of human, ecological, or socioeconomic systems in areas potentially affected by these hazards defines exposure. Meanwhile, vulnerability encompasses the probability that exposed systems will experience impacts from hazards, considering their inherent characteristics including sensitivity and adaptive capacity. Through comprehensive evaluation of these three elements and their complex interactions, the IPCC's framework establishes a foundation for comprehending climate change impacts while informing the development of effective adaptation and mitigation strategies (IPCC, 2014).

The AR6 represents a further evolution of the IPCC's risk assessment framework, with particular emphasis placed on resilience as a crucial factor in addressing climate-related risks and impacts (Figure 4; IPCC, 2023b). This latest iteration illuminates the dynamic relationship between resilience strategies and the fundamental components of risk assessment—hazard, exposure and vulnerability—collectively termed "climate resilient development". The updated conceptual framework emphasizes the necessity of adopting an integrated approach to strengthen resilience against climate change impacts, acknowledging the intricate relationships among climate hazards, exposure levels, and existing vulnerabilities (IPCC, 2021).

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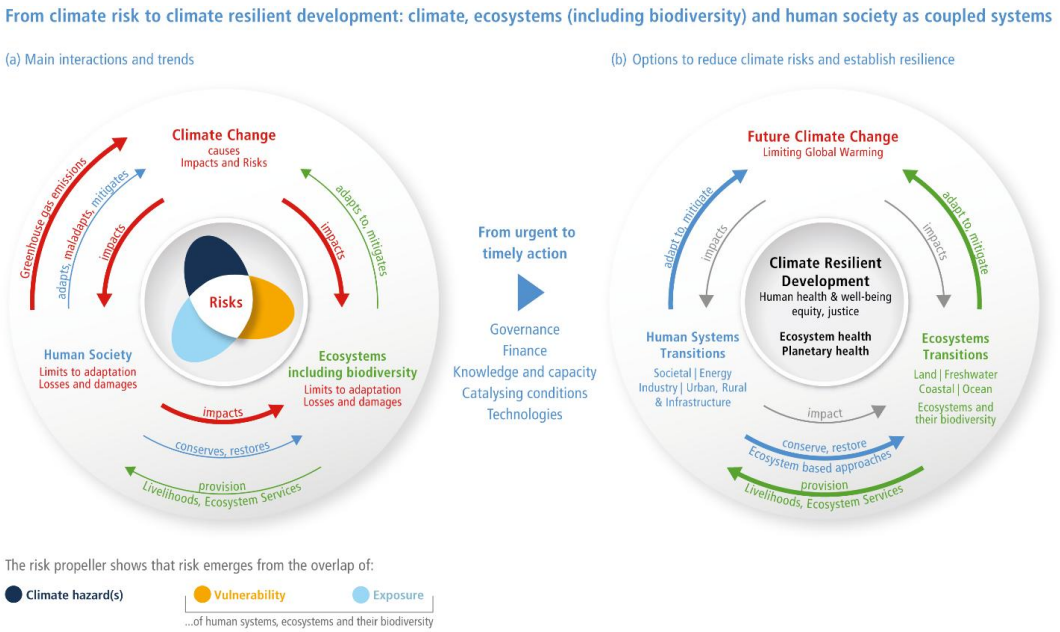

Figure 4. Conceptual framework for climate risk/impacts assessment and «climate resilient development » implementation in AR6. (IPCC, 2023b)

The methodology presented is based on the climate risk evaluation framework established by the ICARIA project (Figure 5; ICARIA, 2023). This framework outlines the procedure for assessing climate-related risks, their impacts on various sectors and systems, and the importance of implementing measures to build resilience. The evaluation framework offers a solid foundation for understanding the connections between climate threats, the vulnerability of both human and natural systems, existing weaknesses, and strategies to improve resilience.

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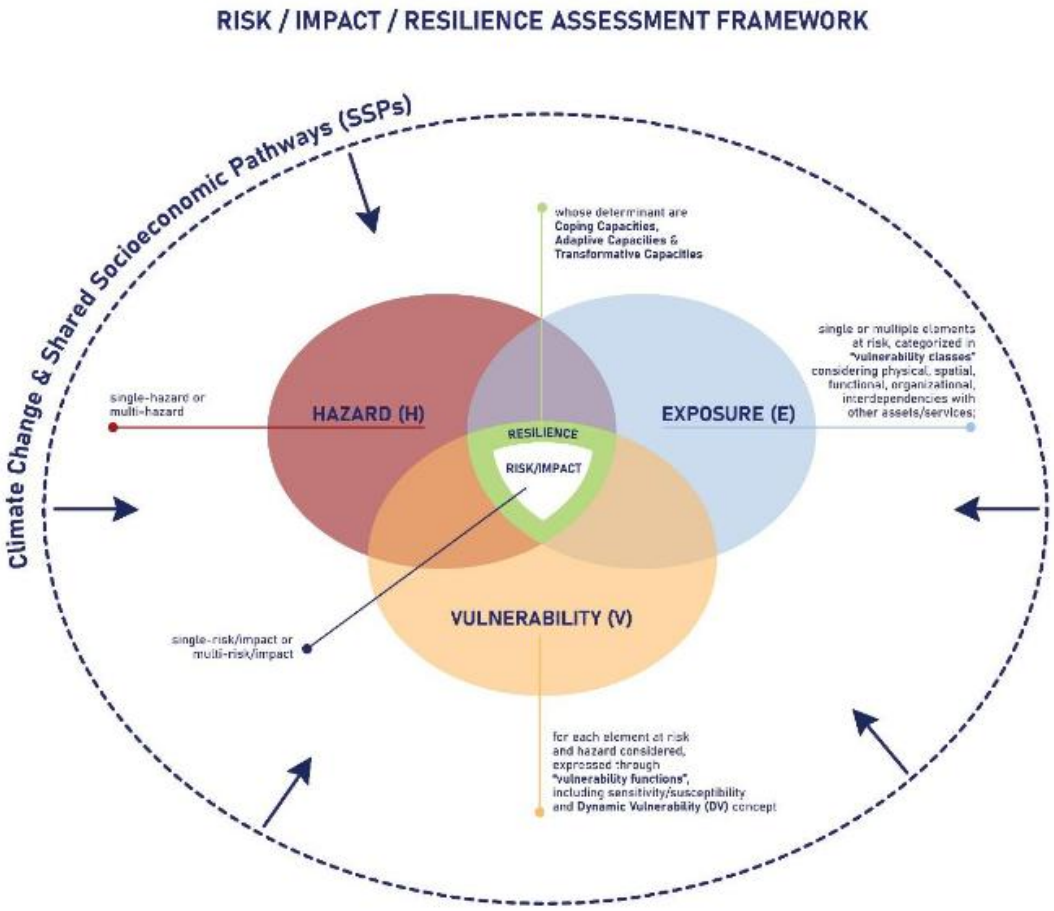

Figure 5. The risk/impact/resilience assessment framework modified from ICARIA [8], consolidated in the field of geophysical hazards ([4]; updated by the UNDRR, 2017 terminology) and harmonized in the context of climate change [1] introducing the resilience components.

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The risk assessment depends on the following factors:

Hazard: The potential manifestation of a naturally occurring or human-induced phenomenon that could result in fatalities, injuries, or additional health consequences, along with harm and losses to assets, infrastructure, means of subsistence, service delivery, ecological systems, and environmental assets. Within the IPCC framework, this term typically denotes "climate-associated physical phenomena or patterns or their material consequences" (IPCC, 2014). This is affected by climatic parameters and site-specific factors that may intensify hazard severity. For instance, the impact of impervious surfaces and human-made changes to river and coastal systems on flood risks or the urban heat island phenomenon's influence on extreme temperature events or. This determination should account for the likelihood of occurrence of associated compound phenomena. As a climate adaptation strategy, Nature-based Solutions can help diminish the severity or probability of these hazards through different pathways.

Exposure: Assessment of the amount, characteristics, and susceptibility of at-risk components (such as populations, structures, infrastructure, services, operations, etc.) that face hazards, considering their geographic and chronological patterns. Exposure is typically integrated with the vulnerability and capabilities of these components to measure the risks/impacts linked to one or multiple hazard events (IPCC, 2014). This process requires developing an extensive inventory of vulnerable assets and services, incorporating all pertinent data that facilitates vulnerability analysis for the various hazards under consideration. The inventory should be categorized into vulnerability groups and should emphasize organizational, structural, geographic, and operational interconnections with other assets and services.

Vulnerability: Refers to the tendency or inclination to experience negative impacts. It encompasses various concepts, including sensitivity to damage and a limited ability to manage and adapt (IPCC, 2014) . This involves creating vulnerability functions that link the magnitude of hazards to the expected damage levels for each asset or component within the vulnerability framework. Additionally, it is important to conduct sensitivity and susceptibility assessments, as well as establish dynamic vulnerability functions when appropriate.

Resilience: As defined by the IPCC, refers to “the ability of social, economic, and environmental systems to manage a hazardous event, trend, or disturbance, by responding or reorganizing in ways that preserve their core functions, identity, and structure, while also retaining the capability for adaptation, learning, and transformation. This includes the implementation of nature-based solutions (NBS) and other adaptive measures that enhance coping and adaptive capacities for the identified assets and services.

The workflow for risk assessment includes several methodological steps (Figure 6):

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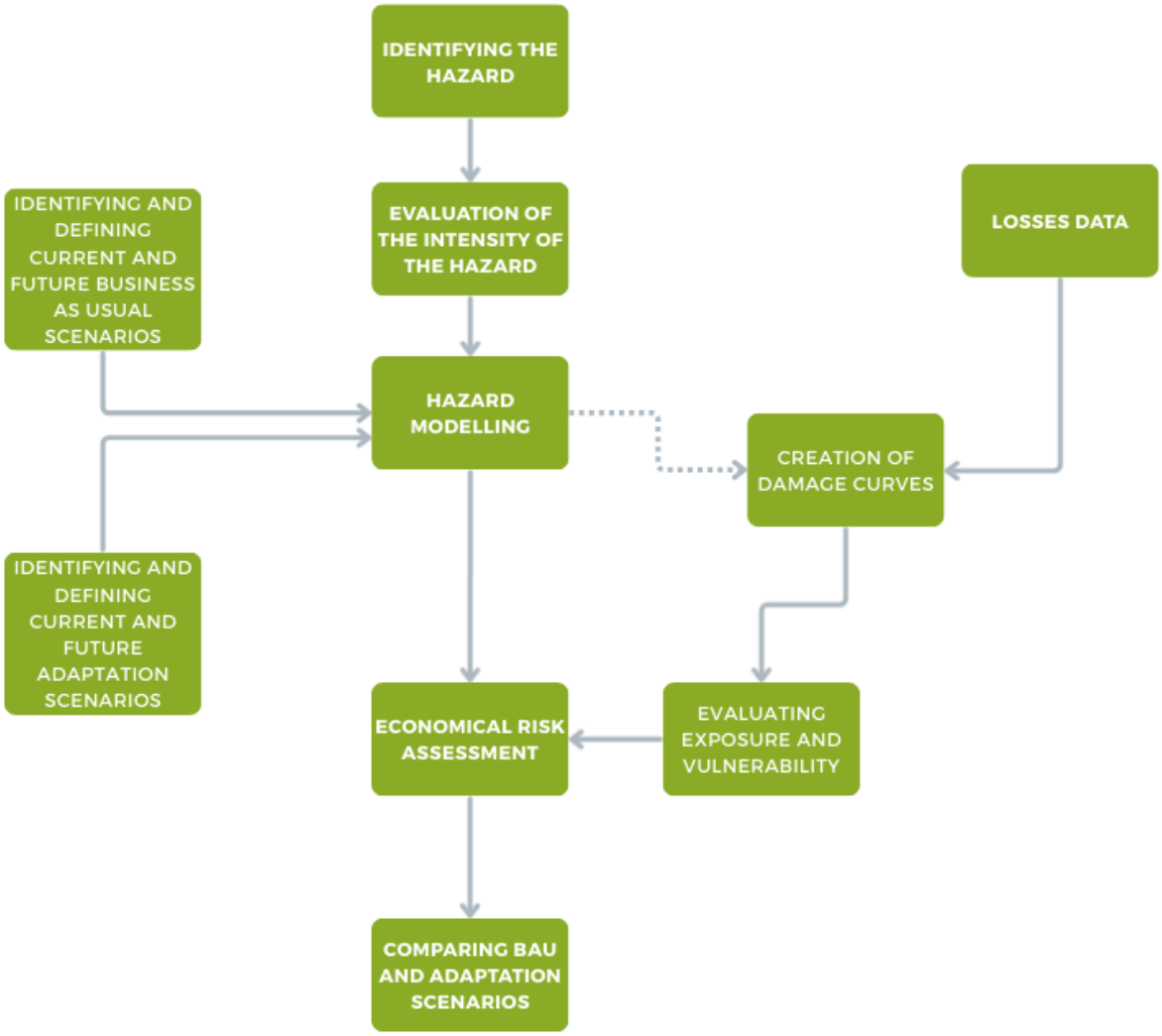

Figure 6. Process to develop a risk assessment including economic damage evaluation

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The first step is to identify the primary hazard or the hazard of interest. This analysis may also consider compound events, highlighting the relationships between different hazards. Once hazards are defined, their intensity is assessed based on required scenarios, utilizing both historical meteorological data and future climate projections, often assigned to specific return periods. A hazard model is then developed and calibrated using historical events and field data.

With these hazard values, along with loss data provided by insurance companies, damage curves are created. We model hazards for the current reference scenario and a Business as Usual (BAU) scenario, which represents future conditions without adaptation measures. During this process, we combine hazard data with exposure and vulnerability through the damage curves to calculate the Expected Annual Damage (EAD). We follow the same steps for scenarios that include adaptation measures. Finally, we compare the results to assess the damage reduction capacity of these adaptation measures.

During this process, one of the key elements is the damage curves and the calculation of the EAD, which are generated by cross-referencing values from the hazard model with data provided by insurance companies. Chapter 3.4 elaborates on this relationship and explains how to obtain these curves and the economic impact.

3.2 Climate-related hazards and key variables and mechanism

Climate hazards present in various forms, each with unique characteristics and effects on human and natural systems. The major categories of these hazards include acute events, such as floods, storms, and heatwaves, as well as chronic hazards like sea-level rise, drought patterns, and changing precipitation regimes. These hazards often interact, resulting in compound events that can intensify their impacts on vulnerable systems.

The inherent complexity of hazards, particularly in our interconnected world, requires systematic methods for their identification and classification. This involves moving beyond isolated analyses to adopt integrated approaches. Historically, risk assessments have focused on single hazards, examining them in isolation. However, it is increasingly acknowledged that real-world scenarios often involve multiple hazards, prompting a crucial shift towards a more integrated perspective.

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Table 2. List of climate related hazards based in the publication Hazard definition & Classification review (UNDRR, 2020)

Hydrologcial	Geotechnical	Environmental
Fluvial Floods	Landslides	Heatwaves
Flash Floods	Catchment erosion	Wind
Drain and sewer flooding	Coastal erosion	Wildfires
Groundwater floods	Riverbank erosion	Biodiversity loss
Coastal floods		Water pollution
Drougths		Air pollution
		Soil pollution

Multi-hazard approaches specifically select several major hazards that a region may face and consider contexts in which hazardous events might occur simultaneously, sequentially, or cumulatively over time, while considering their potential interrelated effects. This is different from simply overlaying information for multiple single hazards, an approach often called "multi-layer single hazard," which can result in underestimated risks if interrelationships are overlooked.

The interactions between individual hazards during multi-hazard events are complex and can take several forms. These include coincidence hazards, which occur simultaneously in the same geographic region, and consecutive hazards, which happen in a sequence. The timing, order, and intensities of these consecutive events can vary significantly, and they can be either independent or dependent, meaning the impact of one hazard can influence a subsequent one. A particularly critical type of interaction involves cascading effects, where an initial hazard (or trigger event) leads to a series of secondary failures or subsequent hazards. These effects can extend across geographical, administrative, and sectoral boundaries due to interconnected systems. For example, an earthquake might trigger landslides, or a drought may increase surface runoff during heavy rainfall, leading to deeper floods.

Various methods are used to study these multi-hazard interrelationships, including narrative descriptions, hazard wheels, matrices, network diagrams, hazard maps, and more advanced probabilistic and systems-based modeling.

To effectively assess hazards, they must be characterized by several measurable variables that describe their properties and potential impacts. The intensity or magnitude of a hazard quantifies its potential to affect the environment and engineered systems. Spatial and temporal components are fundamental to hazard characterization. The location or spatial extent defines the geographical area impacted by a hazard event, while duration refers to how long the event lasts—such as the average duration of 61 days for

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droughts. Frequency or probability of occurrence indicates how often an event is expected to take place within a given timeframe and space; hazard curves are commonly used to illustrate the probability of exceedance as a function of intensity. The rate of onset describes whether an event occurs slowly (like a drought) or suddenly (like a flash flood). Additionally, actions refer to specific ways a hazard manifests and interacts with structures, such as scouring, debris impact, buoyancy, and hydrodynamic forces in the case of floods.

Importantly, hazards and their characteristics are not static; they possess a dynamic nature subject to change over time due to factors such as climate change, land-use transformations, population dynamics, and the implementation of adaptation measures—all of which can alter their magnitude, duration, and likelihood.

3.3 Data inputs

Comprehensive risk assessment for climate adaptation relies on robust data inputs. Essential data include vulnerability indicators for infrastructure and communities, local climate projections, and exposure metrics. These data sets identify priority areas for adaptation by detailing heat stress patterns, flood-prone zones, and drought susceptibility. Socioeconomic data, such as insurance data loses, population demographics, economic activities, and adaptive capacities, inform assessments of community resilience and guide the design of targeted adaptation strategies. Infrastructure data, including building conditions, urban planning parameters, and critical facility locations, support the evaluation of structural vulnerabilities and adaptation planning. Integrating these diverse data sources enables decision-makers to assess the cost-effectiveness of adaptation options, prioritize interventions, and formulate evidence-based policies. Monitoring and evaluation data further track the outcomes of adaptation measures and inform adaptive management. Inadequate data inputs reduce the precision of adaptation planning and may lead to maladaptation.

Various regional, national, and European sources provide hazard data, particularly for flood-related hazards such as fluvial floods, coastal floods, and sea level rise. However, these models are generally broad in scope, utilize coarse spatial resolution, and focus on return periods derived from historical records, which limits their calibration with historical loss data. There is a notable absence of spatially explicit hazard values for individual events. Furthermore, pluvial flood maps are rarely available, despite the significant losses associated with pluvial flooding. Publicly accessible data for other hazards, including heatwaves and wind events, remain limited. Figure 7, Figure 8 and Figure 9 highlight the information available in 4 CS of the SOTERIA project.

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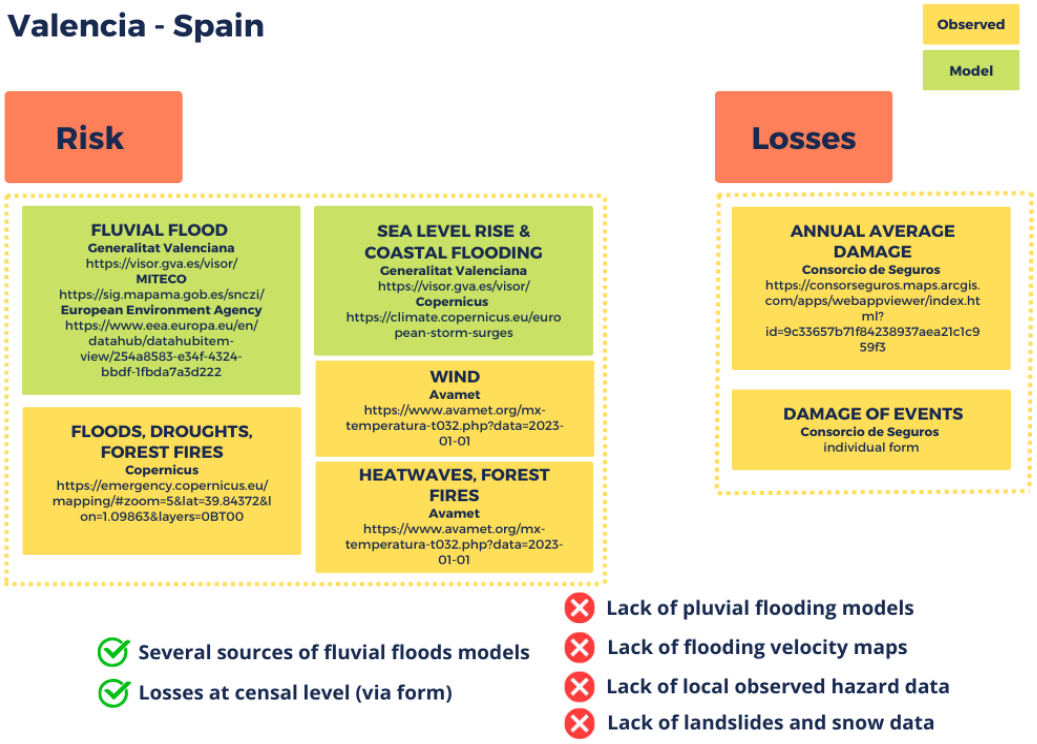

Figure 7. Available data on climate risk and losses in CS Valencia, Spain.

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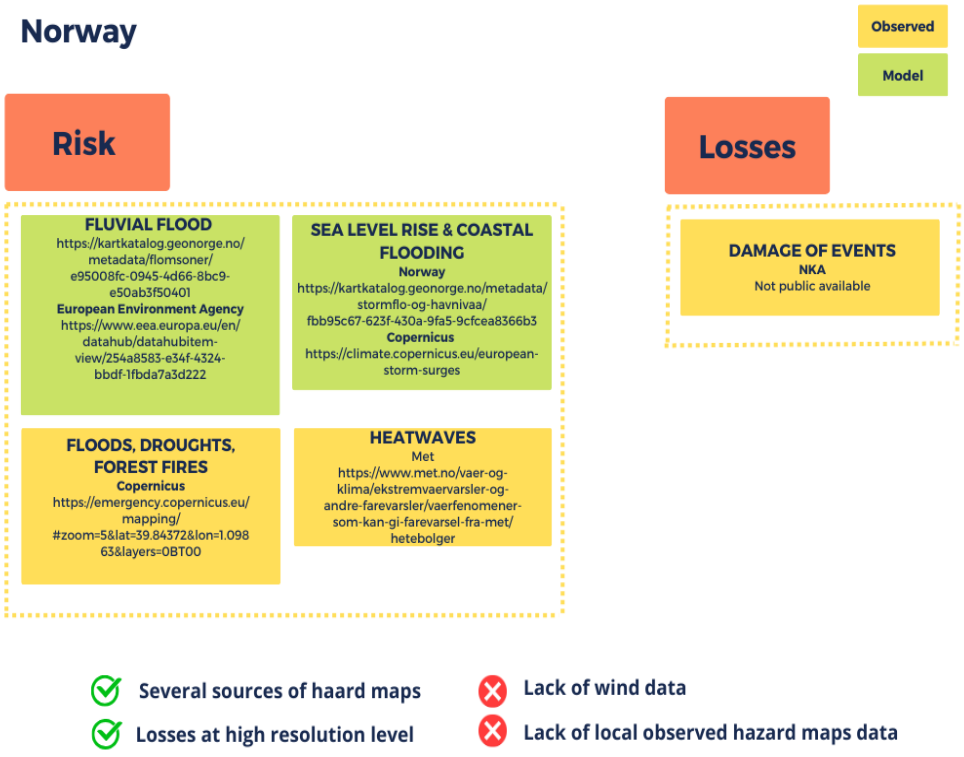

Figure 8. Available data on climate risk and losses in CS Norway.

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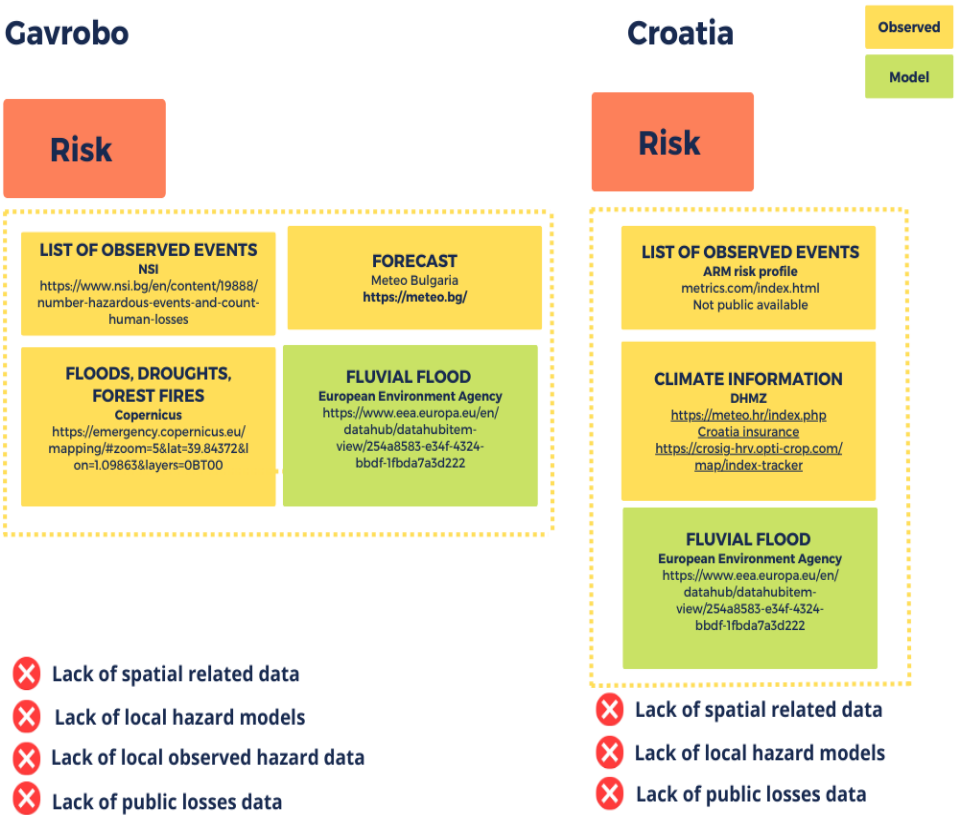

Figure 9. Available data on climate risk and losses in CS Gabrovo and Croatia.

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The data required for a comprehensive risk assessment can be classified into three primary categories. **Geographic data** includes digital terrain models (DTM), digital elevation models (DEM), digital surface models (DSM), land use and land cover maps, infrastructure networks such as roads, utilities, and communications, urban planning maps, satellite imagery, aerial photography, and geological and soil maps. **Climatic data** consists of temperature records, precipitation patterns and intensity, wind speed and direction, humidity levels, historical weather events and extremes, climate change projections, return periods for extreme events, and seasonal variations. **Exposure and vulnerability** data comprises cadastral information, property records, building characteristics, construction types, population demographics and distribution, critical infrastructure locations, socioeconomic indicators, historical damage and loss records, insurance data, claim history, emergency response capabilities, population vulnerability factors including age, health, and income, as well as economic assets and their value. Collectively, these datasets support detailed risk analysis and inform the development of targeted mitigation strategies.

3.4 From hazard maps to Expected Annual Damage through damage curves

Economic damage assessment is essential for effective flood risk management and is becoming increasingly important in urban planning, particularly in the context of adapting to climate change. As discussed in Chapter 2, much of the literature surrounding damage curves focuses specifically on floods. Floods are consistently recognized as the most damaging natural hazard in Europe, and their economic impact is expected to increase due to climate change (Martínez-Gomariz et al., 2020). This change is likely to lead to more frequent and intense flooding events, alongside growing urbanization in flood-prone areas. In this section, floods will be used as an example, but this methodology applies equally to any type of climate hazard. This section outlines a methodology for quantifying these economic impacts, concentrating on the transition from hazard maps to the calculation of EAD using damage curves.

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Figure 10. Process of calculation of EAD through damage curves.

3.4.1 Understanding hazards and damage models

Damage can be categorized in two main ways: tangible (economic) damage and intangible damage (such as loss of life and health impacts). Additionally, damages can be classified as direct damages (like property damage) and indirect damages (such as business interruptions) (Figure 11, Nicklin et al., 2019). The primary objective of damage models is to evaluate the cost-effectiveness of various projects and strategies aimed at mitigating the impacts of climate hazards (Martínez-Gomariz et al., 2020).

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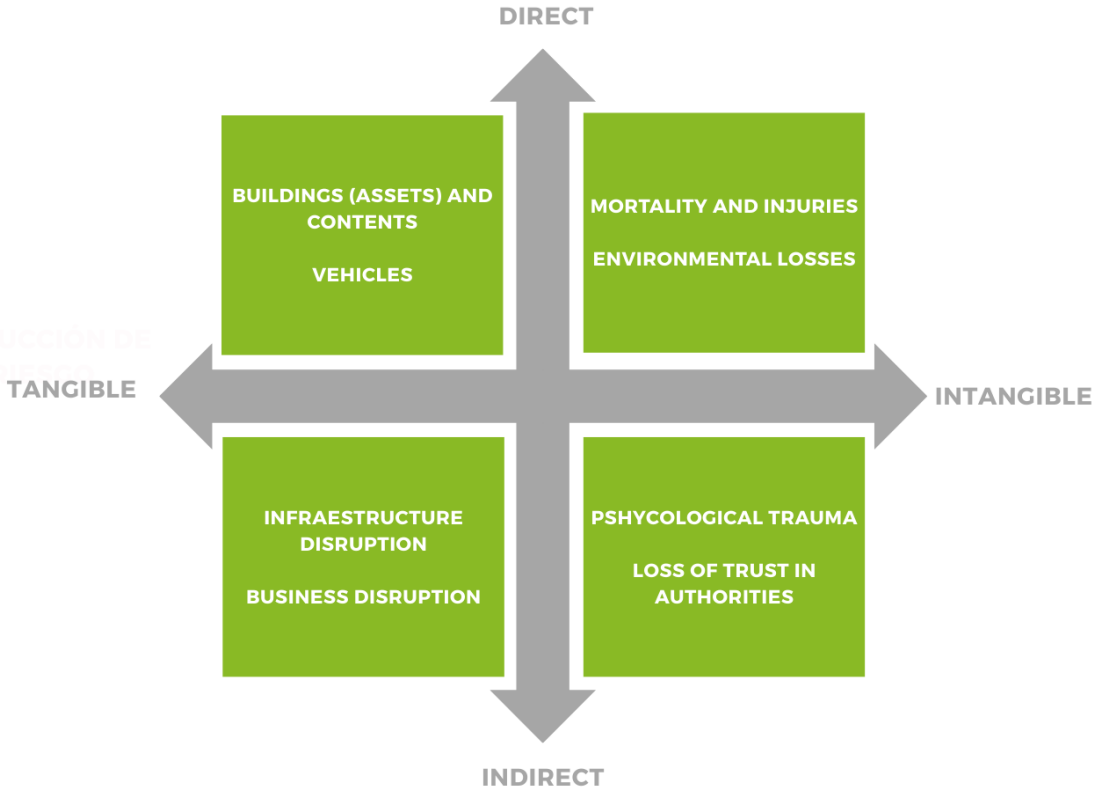

Figure 11. distinction between tangible, intangible, direct, and indirect flood damage. Based in Nicklin et al. (2019)

At the core of most damage assessment models are depth-damage curves, also known as vulnerability or stage-damage functions (Martínez-Gomariz et al., 2020). These curves illustrate the relationship between the severity of a hazard (for instance, water depth for flood events or wind speed for wind events) and the expected economic damage to specific assets or types of land use (Figure 12, European Commission. Joint Research Centre., 2016).

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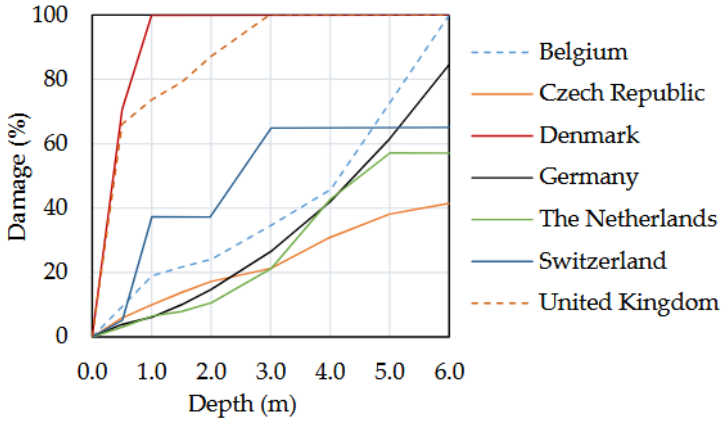

Figure 12. Residential depth-damage curves for European Countries proposed by Huizinga (European Commission. Joint Research Centre., 2016)

Damage curves can be categorized based on their structural characteristics and the way they represent damage. Relative damage curves quantify damage as a percentage of the total value of the property or asset (Martínez-Gomariz et al., 2020). This method offers the advantage of being more universally applicable across various locations and time periods since it does not rely on local market values, which can fluctuate significantly. In contrast, absolute damage curves provide a straightforward monetary representation of damage, expressed in specific monetary units (e.g., €/m²) (Martínez-Gomariz et al., 2020). However, these curves necessitate periodic recalibration to accommodate for factors such as depreciation of the asset and inflation over time, making them less adaptable to changing economic conditions.

The development of damage curves employs several methodologies, each with its distinct advantages. Analytical curves are produced in controlled laboratory settings, where researchers rigorously evaluate related variables like water depth, wind velocity or duration of exposure in a extreme events (Martínez-Gomariz et al., 2020). This precise monitoring allows for a detailed understanding of how different conditions affect property damage.

Empirical curves, on the other hand, are derived from real-world data. They are created by collecting information from property damage surveys conducted in the aftermath of previous extreme events or insurance sector data collection (European Commission. Joint Research Centre., 2016). By analyzing actual

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incidents, these curves capture the realities of how assets are damaged under specific conditions, providing valuable insights for future predictions.

Synthetic functions are another approach, relying on theoretical models structured around a standard property type. These functions are particularly useful when actual damage data is scarce or unavailable. They provide a theoretical framework for understanding potential damage impacts based on established properties (Martínez-Gomariz et al., 2020).

Many contemporary methodologies take a hybrid approach, integrative analytical, empirical, and synthetic techniques to generate semi-empirical curves. This combination enhances the reliability and applicability of the damage curves across different scenarios.

Furthermore, it is crucial to distinguish between the types of damage incurred: damage to the building structure (which includes critical components such as foundations, walls, and electrical systems) and damage to contents or inventory (which encompasses items like furniture, household equipment, and merchandise) (Martínez-Gomariz, Locatelli, et al., 2019; Martínez-Gomariz et al., 2020). This distinction is essential, as various components can suffer different levels of damage under identical exposure conditions. Understanding these differences allows for more accurate assessments of climate impacts and better-informed decisions regarding risk management and recovery efforts.

3.4.2 From hazard maps to property-level damage estimation

The initial input for damage assessment is usually a hazard map, which provides spatially distributed information on the maximum hazard levels across an exposed area, often derived from hazard models (Locatelli et al., 2020; Martínez-Gomariz et al., 2020; Martínez-Gomariz, Guerrero-Hidalga, et al., 2019). A significant challenge arises in the case of urban pluvial (rainfall-induced) floods: the water depth on the streets often differs greatly from the water depth inside properties. This discrepancy is mainly due to the relatively short duration of water presence during pluvial events, which may not allow enough time for the external and internal water levels to equalize (Martínez-Gomariz, Guerrero-Hidalga, et al., 2019).

To address this issue, a conceptual model is used to translate external street water depths into expected internal water depths (Martínez-Gomariz, Guerrero-Hidalga, et al., 2019):

- **Entrance Elevation** (Steps): The presence and height of steps or elevation changes at property entrances (which may be absent in many commercial buildings but are typically higher for residential homes) serve as protective barriers that limit water entry.

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- **Sealing Coefficient** (SC): Another crucial factor is the permeability of the property's enclosures, such as doors, windows, and drains. The Sealing Coefficient (SC) relates the external water depth to the expected internal depth, acknowledging that more permeable enclosures allow for greater water ingress.

- **Potentially flooded surface**: For properties with large floor areas, such as hospitals and large commercial centers, it is important to note that not the entire surface may become inundated, even if water does enter. Functions are utilized to estimate the actual potentially inundated areas within the property based on the external water depth and the total floor area.

Once the estimated internal hazard value for a specific property is determined, the appropriate depth-damage curve for that type of property (such as residential, commercial, or industrial) and asset type (including buildings, furniture, and inventory) is applied (Martínez-Gomariz et al., 2020; Martínez-Gomariz, Guerrero-Hidalga, et al., 2019).

It's important to understand that maximum damage does not always reach 100% for all asset types. For buildings, many components, including foundations, structural elements above the ground floor, and concrete or brick walls—are often considered "undamageable" or less prone to total loss, even in extreme events. In the case of floods, for example, the maximum damage for residential properties can be around 34%, for industrial properties about 30%, and for office buildings approximately 36%. In contrast, contents and inventory, especially those not stored in cold storage or placed on elevated shelves, may suffer damage levels reaching up to 100% (Locatelli et al., 2020).These selections are then applied via sector-specific depth–damage functions; Valencia’s curves provide a working example for residential, commercial and industrial assets (Figure 13).

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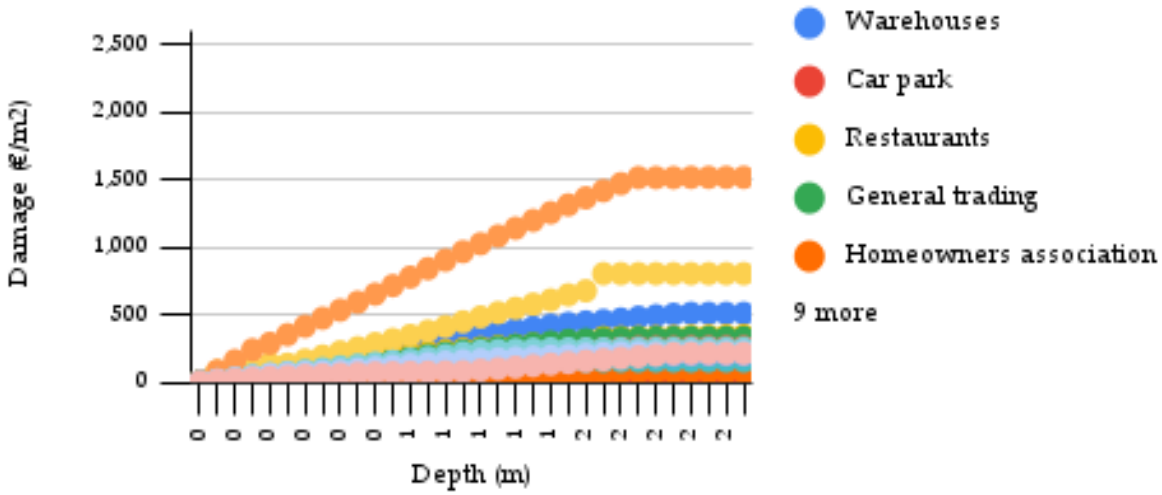

Figure 13. Flood damage curves by sectors in the Case Study of Valencia (RESCCUE, 2020)

3.4.3 Aggregating damage and calculating expected annual damage (EAD)

After calculating the damage for individual properties and their assets, the total direct damage from a specific flood event is determined by aggregating these values. This process involves summing the losses across all affected buildings, vehicles, and urban infrastructure (Locatelli et al., 2020). In addition to direct damage, indirect damage such as business interruptions and impacts on coastal economies due to polluted water—are also quantified and monetized. For example, indirect flood damages resulting from business interruptions can be estimated as a percentage of direct damages (e.g., 29%) (Locatelli et al., 2020).

To calculate the EAD, damages are estimated for various design extreme events with different return periods (such as 1, 10, 50, 100, and 500 years). EAD represents the area under the damage versus exceedance probability curve, indicating the average annual economic loss from floods over an extended period (Figure 14). This comprehensive approach allows for a robust assessment of risk, providing a monetary value for average annual damages (Locatelli et al., 2020).

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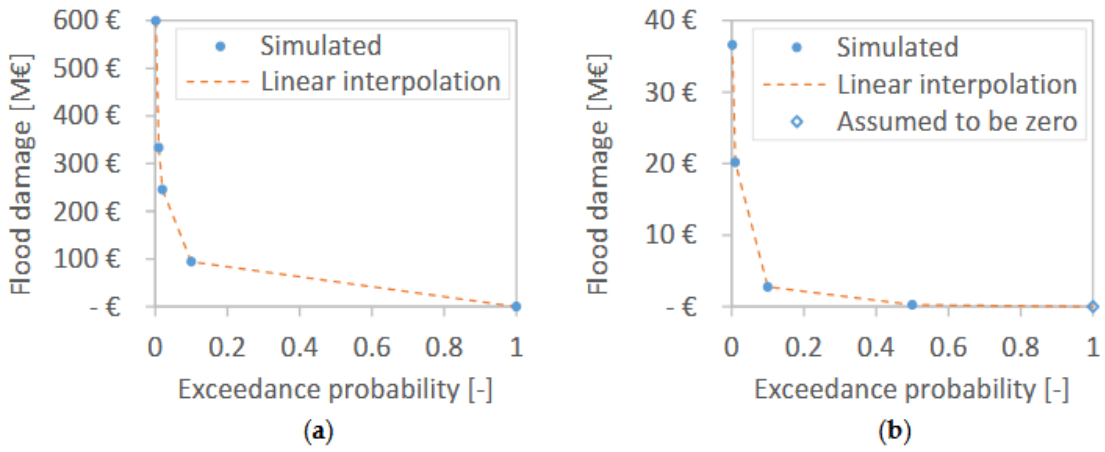

Figure 14. Example of flood damage as a function of the excedance probability in barcelona (a) and Badalona (b) (Locatelli et al., 2020). The EAD is the value of the area below the linear interpolation.

3.4.4 Addressing uncertainties and ensuring transferability

Damage assessment is inherently uncertain due to various factors. Model assumptions contribute to this uncertainty, as, for instance, hydrodynamic models often require simplifications, such as roughness coefficients and hydrological losses in green infrastructure. Similarly, damage models use parameters that influence indoor water level exchange. These simplifications can lead to discrepancies between modeled results and actual outcomes (Locatelli et al., 2020).

Data limitations also play a significant role in assessment accuracy. The completeness of climate data, insufficient simulation points in EAD calculations, and the level of detail in exposure data—such as relying on generalized land use information instead of individual building footprints—impact the reliability of assessments (European Commission. Joint Research Centre., 2016; Locatelli et al., 2020). Additionally, expert judgment is a double-edged sword; while expert input is essential for addressing data gaps and refining damage curves, it inevitably introduces a degree of subjectivity (European Commission. Joint Research Centre., 2016; Martínez-Gomariz et al., 2020).

To enhance the applicability and comparability of damage assessments across different regions, two key concepts are employed. The first is regional transferability. The shape of relative damage curves

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(expressed as percentage damage) tends to remain consistent across highly urbanized areas within a country like Spain, as construction types and damage mechanisms are similar. However, converting these relative damages into absolute monetary values (€/m²) requires consideration of local economic conditions (Martínez-Gomariz et al., 2020; Martínez-Gomariz, Guerrero-Hidalga, et al., 2019).

Regional adjustment indices (RI) are calculated using demographic, economic, and geographical factors that affect the prices of goods and services in a specific municipality compared to a reference city. Key indicators for these indices include the average tax value per square meter of buildings, disposable income for residential furnishings, average revenues or investments, and the number of businesses in the commercial and industrial sectors (Martínez-Gomariz et al., 2020).

According to the European Commission (2016) the methodology for extrapolating flood damage curves to different countries combines continent-specific average damage curves with country-specific maximum damage values. This approach was developed to address the inconsistencies in methodologies across various countries and to establish a globally consistent database for assessing flood damage.

The continent-specific damage curves are derived from an extensive global literature review of quantitative flood damage data. These curves are normalized to reflect fractional damage (ranging from 0 to 1) based on water depth for various damage categories, including residential buildings, commerce, and industry. They capture the shape of the damage function.

For monetary differentiation of damage across countries, national maximum damage values are determined. For buildings (residential, commercial, and industrial), these values are generated through regression analysis of construction costs obtained from international surveys conducted by multinational construction companies like Turner & Townsend and EC Harris, correlated with national socioeconomic parameters, primarily GDP per capita from the World Development Indicators. For infrastructure, average values from European studies are used and adjusted based on GDP per capita, while for agriculture, maximum damage is linked to "value added per hectare."

Additionally, the methodology provides guidance for adjusting these curves and maximum values to reflect specific local conditions, such as depreciation, inclusion of contents, building materials, and the differences between urban and rural or formal and informal settlements.

Temporal transferability is also critical for estimating damages from future flood events. Damage costs must be adjusted over time, which is achieved through temporal adjustment indices (TI). These indices are developed using long-term economic forecasts, such as real GDP growth, enabling current damage costs

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to be updated to reflect future estimates. The total adjustment index (TAI), which combines both RI and TI, allows for the modification of monetized asset curves for any given municipality and future year (Martínez-Gomariz et al., 2020).

Finally, validating the calculated damages against actual observed damages or compensation data, such as those from insurance consortiums like the Spanish CCS, is essential (European Commission. Joint Research Centre., 2016). Typically, calculated damages exceed compensations—by about 21-31% in tested Spanish cases—due to factors like uncompensated damages, uninsured properties, underinsurance, deductibles, and non-structural elements like gardens that are not covered. This comparison provides crucial feedback on model performance (Martínez-Gomariz, Guerrero-Hidalga, et al., 2019). The iterative process of development, application, and validation ensures the continuous improvement and reliability of damage assessment methodologies.

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4. Climate change

4.1 The role of climate change in risk assessment

Climate change has become a crucial factor in risk assessment, primarily due to the rising losses linked to climate-related events. Since the 1980s, the number of natural disasters with significant economic impacts has tripled, and this trend is expected to continue (Ingels et al., 2024). As more people live in areas prone to hazards, the potential for substantial losses increases. For the insurance sector, understanding and managing these evolving risks is essential for its long-term sustainability and its capacity to provide financial protection to society.

Recent comprehensive analyses of climate change, particularly those presented in the latest IPCC Assessment Report (IPCC, 2023a), reveal increasingly concerning trends in global climate patterns. The data paints a clear and troubling picture of accelerating environmental changes that demand immediate attention. Global temperature measurements demonstrate an unmistakable upward trajectory, with current data showing a 1.1°C increase from pre-industrial levels. This warming trend is particularly evident during the 2011-2020 period, which stands as the warmest decade on record.

Looking ahead, climate models project additional warming ranging from 1.0°C to 5.7°C by 2100 (IPCC, 2023a). The variation in these projections largely depends on future greenhouse gas emission scenarios and human activity patterns. The impact of these temperature changes has led to significant alterations in global precipitation patterns. While mid and high-latitude regions are experiencing notably increased rainfall, subtropical and tropical areas are facing substantial decreases in precipitation levels. This redistribution of rainfall patterns has significant implications for agriculture, water security, and ecosystem stability worldwide (IPCC, 2023a).

Additionally, the frequency and intensity of extreme weather events have markedly increased. These events include more severe heatwaves, intense storms, devastating floods, and prolonged droughts, all of which pose substantial risks to human communities and natural systems. Advanced climate models, utilizing the latest CMIP6 data and incorporating various SSP scenarios, indicate that extreme precipitation events will become more common. The models show significant changes in both 10-year and 50-year return periods for extreme weather events, suggesting a future marked by more frequent and severe climate-related challenges (IPCC, 2023a).

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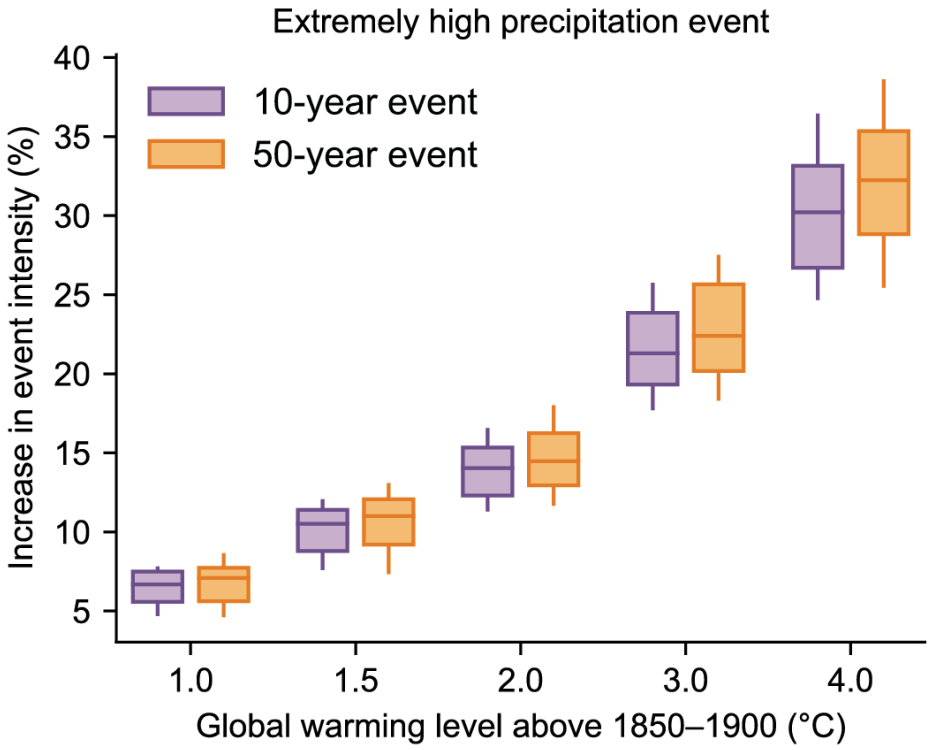

Figure 15. Projected changes in the intensity of extreme precipitation events under 1°C, 1.5°C, 2°C, 3°C, and 4°C global warming levels relative to the 1850–1900 baseline (IPCC, 2023a).

One of the most pressing concerns emerging from current research is the accelerating rise in global sea levels. This rise is driven by two primary factors: the increasing rate of glacial and ice sheet melting, and the thermal expansion of ocean waters as they warm. Current scientific projections indicate potential sea level increases between 0.28 and 1.01 meters by 2100, though these estimates are dependent on future emission scenarios and the behavior of the Antarctic ice sheet. The uncertainty in these projections largely arises from complex feedback mechanisms and potential tipping points in the Earth's climate system.

These findings collectively underscore the urgent need for comprehensive climate action and adaptation strategies. The data suggests that even with immediate and substantial reductions in greenhouse gas emissions, some degree of climate change impact is now unavoidable. This necessitates both mitigation

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efforts and adaptive measures to address these evolving environmental challenges. The situation calls for coordinated global action, innovative technological solutions, and significant policy changes to confront what has become one of the most pressing challenges of our time.

4.1.1 RCP-SPP framework

A significant advancement in climate risk assessment is the adoption of forward-looking models. Currently, less than half of the existing studies on climate risk insurance incorporate climate change scenarios, and an even smaller percentage consider socioeconomic development scenarios (Ingels et al., 2024). It is crucial for models to provide a thorough analysis of RCPs and SSPs. These frameworks are essential for understanding and projecting future climate scenarios (NATALIE, 2024).

RCPs, adopted by the IPCC's Fifth Assessment Report, are complex trajectories of greenhouse gas concentrations that serve as crucial tools for climate scientists and policymakers worldwide.Figure 16 visualises the four RCPs by total radiative forcing to 2100, providing a quick map from pathway name to forcing level. These pathways allow for modeling and projecting potential future greenhouse gas emissions and their consequences. The IPCC has established four primary RCPs: RCP2.6, RCP4.5, RCP6.0, and RCP8.5. Each represents distinct potential global warming outcomes by the end of the century, ranging from optimistic projections of less than 2°C warming to more severe scenarios exceeding 4°C. RCP 8.5, in particular, is considered the most extreme high-emissions scenario, developed using CMIP5 models.

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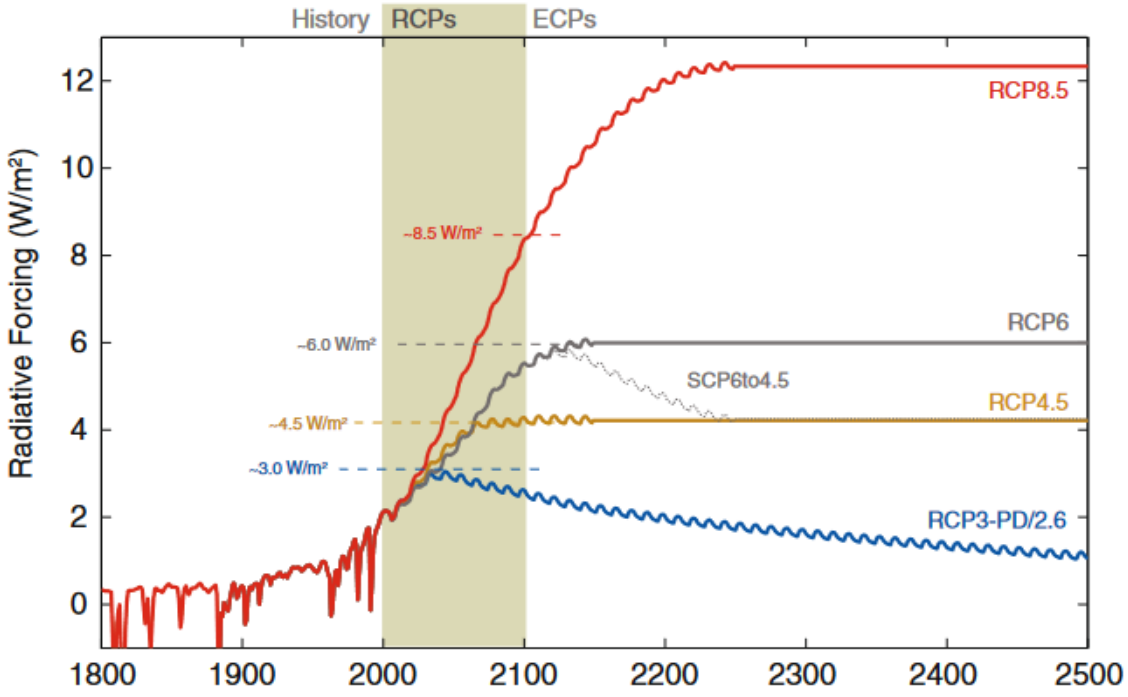

Figure 16. Representation Concentration Pathways (RCP)(Meinshausen et al., 2020). Total radiative forcing (anthropogenic plus natural) for RCPs, -supporting the original names of the four pathways as there is a close match between peaking, stabilization and 2100 levels for

SSPs represent a more recent and advanced approach introduced by CMIP6, significantly expanding and refining the methodologies used in CMIP5. These pathways provide a highly detailed framework for understanding potential future emission trajectories by incorporating various socioeconomic factors. This includes considerations of population growth patterns, economic development trajectories, technological advancement rates, and social change dynamics. The SSPs are organized around five distinct socio-economic storylines, each presenting unique challenges and opportunities for climate change adaptation and mitigation.

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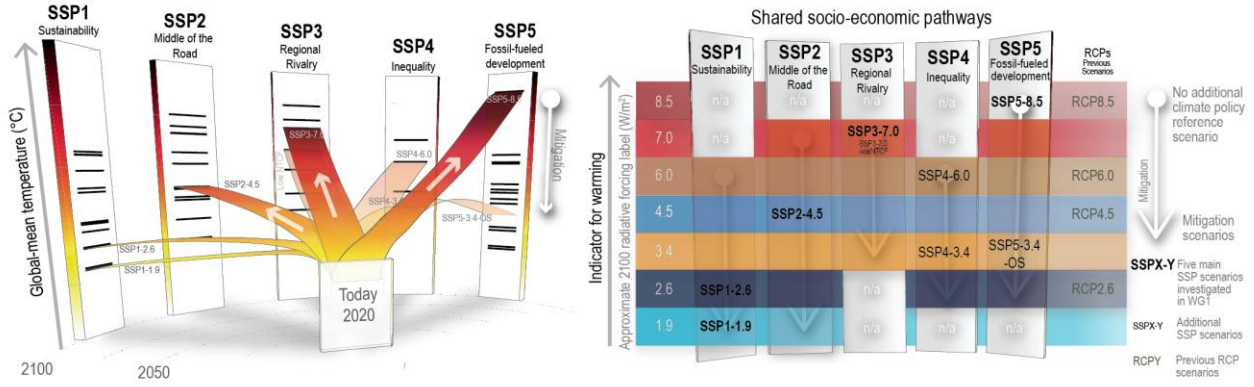

Figure 17. The SSP scenarios used in this Report, their indicative temperature evolution and radiative forcing categorization, and the five socio-economic storylines upon which they are built (IPCC, 2023a) .

For example, SSP1 envisions a world moving towards sustainable practices, characterized by inclusive development and strong environmental awareness, which results in minimal challenges for both mitigation and adaptation efforts. In contrast, SSP3 outlines a more difficult scenario of 'regional rivalry,' where international cooperation is limited and environmental concerns take a back seat.

The SSP-RCP Framework integrates these two approaches to create a comprehensive tool for assessing the impacts of climate change and evaluating various adaptation and mitigation strategies. This combined framework generates a detailed scenario matrix, allowing researchers and policymakers to investigate climate change effects under diverse socioeconomic and emission conditions. For instance, a scenario combining RCP 8.5 with SSP3 would depict a future with high greenhouse gas emissions and limited international collaboration, likely resulting in severe climate impacts. Conversely, the combination of RCP 2.6 with SSP1 would suggest a more optimistic future characterized by aggressive mitigation efforts and sustainable development practices.

The temperature projections linked to these combined scenarios can extend beyond the range previously covered by RCP-only scenarios, presenting a more comprehensive picture of possible future outcomes.

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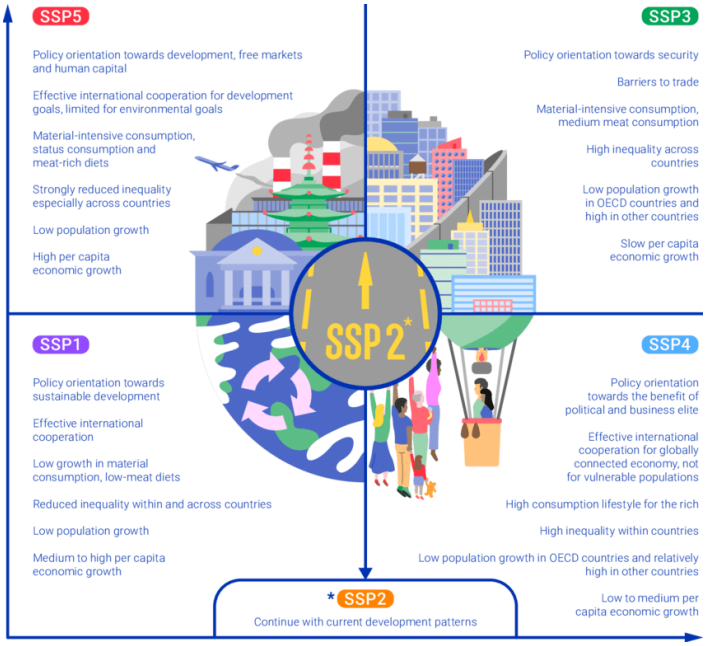

Figure 18. Shared socioeconomic pathways (in the figure, OECD stands for Organization for Economic Co-operation and Development). Adapted from (O'Neill et al., 2020).

4.1.2 Including climate and socio-economic scenarios under risk assessment

The IPCC is a leading organization in the coordination and assessment of global climate science. In its recently released AR6, the IPCC provides authoritative analyses of climate change based on the latest research and modeling advancements.

A key component of this work is the Coupled Model Intercomparison Project (CMIP), which has significantly evolved since its inception in 1995. The current version, CMIP6, marks a major advancement in climate modeling. It employs sophisticated Earth System Models (ESMs) that integrate interactions among the atmosphere, land, and ocean with unprecedented detail. These models have improved spatial resolution and can represent atmospheric circulation patterns more effectively than earlier models.

One of the noteworthy innovations in CMIP6 is the shift from RCPs to SSPs. SSPs offer more comprehensive scenarios by combining projections of societal development with emission pathways. The enhanced

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capabilities of CMIP6 models have revealed that climate change impacts could be more severe than previously anticipated, making them essential tools for future risk assessments and adaptation planning.

As reported in the IPCC's AR6 (IPCC, 2023a), CMIP6 models demonstrate higher spatial resolution and an increased ability to represent atmospheric circulation patterns compared to previous CMIP generations. Moreover, these new models display higher sensitivity and project more severe climate change impacts than anticipated by CMIP5. This enhanced capability provides additional valuable information for further studies and risk assessments.

Climate modeling has advanced significantly, with downscaling techniques becoming increasingly important for converting global climate projections into regional and local scales. There are two primary approaches to downscaling: dynamical and statistical, each offering unique advantages for assessments of climate impact.

Dynamical downscaling utilizes high-resolution Regional Climate Models (RCMs) that are nested within Global Climate Models (GCMs), typically operating at resolutions of 10 to 50 kilometers. This method explicitly captures atmospheric physics and dynamics at finer scales, considering local topography, land-sea contrasts, and mesoscale atmospheric processes that global models often overlook. Although it requires substantial computational resources, dynamical downscaling provides physically consistent climate variables across various dimensions.

In contrast, statistical downscaling establishes empirical relationships between large-scale climate predictors and local-scale climate variables based on historical observations. This method is more computationally efficient and can be applied to multiple GCM outputs quickly, making it especially useful for assessing uncertainties. Common statistical techniques include weather typing, regression methods, and weather generators.

The choice between these methods often depends on the specific application, available computational resources, and the spatial and temporal resolution needed. Statistical downscaling is particularly beneficial for impact studies requiring point-scale climate information, while dynamical downscaling is preferred in regions with complex topography or when physical consistency among multiple climate variables is essential. Both methods are vital tools for climate adaptation planning, assisting stakeholders in understanding and preparing for local climate change impacts.

The scenarios generated by these models are specifically designed to explore the potential consequences of human-induced climate change, serving as crucial inputs for impact models. Given the advancements

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in CMIP6, there is a consensus among experts that its data should be utilized for future studies and risk assessments, as it offers a more comprehensive and nuanced understanding of potential climate futures (ICARIA, 2023).

4.2 Adaptation measures

As described in the previous chapter “The role of climate change in risk assessment”, the planet faces the increasing impacts of climate change. Adaptation strategies have become essential for building resilient communities and protecting vulnerable populations. This chapter explores two key approaches to climate adaptation: NBS and EWS. Although these strategies differ in their implementation, they share a common goal of reducing climate-related risks and enhancing community resilience, reducing damage

Adaptation measures represent the response to both current climate impacts and expected future changes. They include a wide range of actions, from modifications to infrastructure to changes in policy, all aimed at reducing vulnerability to climate-related hazards. The effectiveness of these measures often hinges on their ability to address multiple challenges at once while offering sustainable, long-term benefits.

The insurance sector plays a vital role in promoting and implementing adaptation measures to address climate change. As climate-related losses continue to rise, insurers face significant challenges in maintaining their business models while providing essential coverage. By supporting and encouraging adaptation strategies, insurance companies can reduce their exposure to climate risks and contribute to greater societal resilience. The unique position—situated at the intersection of risk assessment, financial protection, and loss prevention—makes it an ideal catalyst for advancing efforts in climate adaptation.

This chapter specifically examines how NBS and EWS contribute to climate adaptation by exploring their mechanisms, benefits, the challenges associated with their implementation and the links with the insurance sector. We will analyze their roles in risk reduction, their economic implications, and how they can be integrated into broader climate resilience strategies. By understanding these approaches, we can better appreciate how they complement one another and contribute to a comprehensive framework for climate adaptation.

4.2.1 Nature Based Solutions)

NBS represents a transformative approach to addressing urgent global challenges. These solutions are defined as interventions "inspired and supported by nature," which are cost-effective, provide

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simultaneous environmental, social, and economic benefits, and help build resilience (European Comission, 2021). NBS include actions to protect, sustainably manage, and restore natural or modified ecosystems, effectively tackling societal challenges while delivering benefits for both human well-being and biodiversity (European Comission, 2021).

As an umbrella framework, NBS integrates various ecosystem-based approaches, including Ecosystem-based Adaptation (EBA), Ecosystem-based Disaster Risk Reduction (Eco-DRR), Green Infrastructure (GI), and Water-Sensitive Urban Design (WSUD) (European Comission, 2021; IUCN, 2020). Their multifunctional nature offers a wide array of co-benefits: regulating climate, sequestering carbon dioxide, filtering air and water, mitigating runoff, controlling erosion, and supporting pollination, while also reducing damage from natural disasters (European Comission, 2021; Interreg, s. f.; McPhearson et al., 2023). In urban settings, NBS enhance livability by reducing heat stress and improving human thermal comfort. Ultimately, NBS are considered crucial for addressing the interconnected crises of climate change, disaster risk, and biodiversity loss (European Comission, 2021).

The significance of NBS as climate adaptation measures is especially evident in urban areas, which are increasingly vulnerable to climate hazards like floods, droughts, and heatwaves due to certain urban development patterns (McPhearson et al., 2023). NBS provide affordable and effective protection against extreme weather events, offering flexible and adaptable infrastructure compared to conventional grey infrastructure. They are seen as "safe-to-fail" solutions that can adapt to evolving risk profiles and environmental changes (McPhearson et al., 2023). Their critical role in addressing biodiversity loss and climate change has made them a key focus in international policy, specifically highlighted in important European initiatives like the European Green Deal, the EU Biodiversity Strategy for 2030, and the new EU Strategy on Adaptation to Climate Change (European Comission, 2021; Interreg, s. f.; McPhearson et al., 2023).

The role of NBS in risk assessment

NBS play a crucial role in risk assessment and reduction by addressing the components of hazard, exposure, and vulnerability (IPCC, 2023a). To reduce exposure, NBS act as natural protective barriers; for example, coastal dunes, mangrove forests, and riparian vegetation help shield human settlements and infrastructure from storm surges, coastal erosion, and flooding (Spalding et al., 2014). Hazard reduction through NBS involves ecosystem-based approaches such as wetland restoration, urban greening, and sustainable forest management. These methods effectively regulate water flow, mitigate urban heat island effects, and stabilize soils. As a result, they decrease the frequency and intensity of climate-related hazards

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like floods, droughts, heatwaves, and coastal erosion (Ruangpan et al., 2019). NBS also reduce vulnerability by strengthening the resilience and adaptive capacity of socio-ecological systems. They achieve this by enhancing ecosystem services and conserving biodiversity. Ecosystems that are more biodiverse and healthy tend to be more resilient to disturbances and can recover better from the impacts of climate change (Seddon et al., 2020). Additionally, NBS bolster community resilience by improving human well-being, supporting livelihoods, and fostering social cohesion, which ultimately reduces vulnerability to climate-related threats (Frantzeskaki et al., 2019; Kabisch et al., 2016).

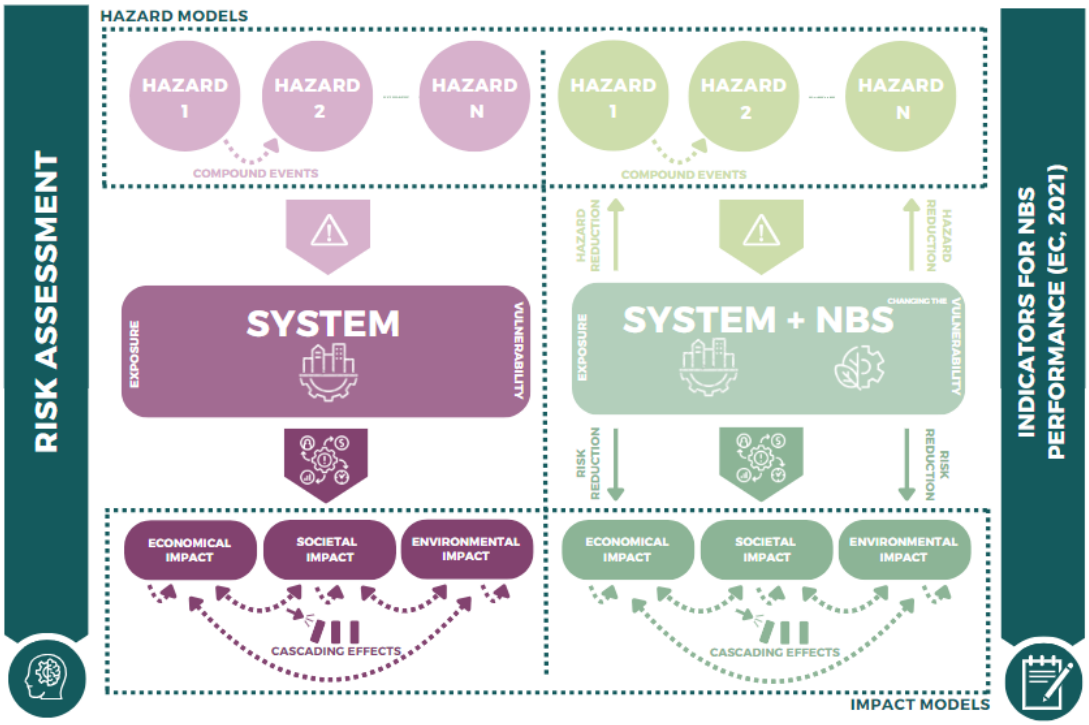

Figure 19. Role of NBS in a common process of risk assessment and risk assessment reduction. (NATALIE, 2024)

In risk assessment processes, NBS address multiple components of a system (Figure 19; NATALIE, 2024) The process begins by identifying the system's assets, services, and the population affected by various hazards. The exposure and vulnerability of the system to these hazards determine the severity of the

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impact. Impacts can be classified into three interconnected categories: economic, social, and environmental. These impacts can create cascade effects; for example, a loss of biodiversity (environmental) can affect agriculture and tourism (economic), which then impacts community well-being (social). It is important to note that biodiversity loss can serve as both an impact and a hazard, depending on the context. The implementation of NBS aims to reduce risk by decreasing vulnerability and the levels of hazards. Additionally, NBS provide co-benefits that can positively influence impacts across all three domains: economic, social, and environmental.

NBS in the insurance sector

Despite the clear benefits and growing recognition of NBS, there remains a significant gap in their widespread integration, particularly in the risk management and insurance sectors. Currently, nature and its inherent risk reduction capabilities are often under-represented or entirely absent from most disaster plans, including crucial Hazard Mitigation Plans (HMPs) (UCSC and USACE, 2024) Additionally, historical research and funding for NBS, especially by the European Commission before 2018, primarily focused on urban challenges, neglecting the equally vulnerable rural mountainous regions exposed to hydro-meteorological hazards (European Comission, 2021). This disconnect results in the multi-faceted benefits of NBS not being consistently reflected in traditional risk assessments.

Although there is increasing interest from the insurance industry in NBS as a risk mitigation strategy, as demonstrated by explorations into the (re)insurance sector's role in disaster risk reduction (European Comission, 2021; Frantzeskaki, 2019), their implementation remains limited—partly due to a perceived lack of robust evidence regarding their effectiveness (European Comission, 2021). To bridge this gap, initiatives such as the "Evaluating the Impact of Nature-based Solutions" handbook have emerged, providing standardized guidance and indicators to build a solid European evidence base on NBS performance and impact (European Commission. Directorate General for Research and Innovation., 2021). Furthermore, a comprehensive assessment of urban nature's holistic value is essential to create a compelling business case for investing in, restoring, and enhancing nature through NBS. This recognition of 'value' should encompass not only the services provided but also the specific needs of the beneficiaries (McPhearson et al., 2023).

To effectively integrate NBS into risk science and the insurance sector, several strategic recommendations are essential. Firstly, there is an urgent need to improve existing risk models by incorporating habitats and wave dynamics more comprehensively, along with expanding their scope to model risks under various climate change scenarios. This also involves developing detailed "vulnerability curves" specifically for

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different habitat types to quantify their protective capacity against hazards (UCSC and USACE, 2024).

Secondly, insurance coverages must be expanded to recognize and protect ecosystems as natural assets. This includes developing pilot projects for resilience insurance, integrating NBS into green building coverage enhancements, supporting catastrophe wrappers for debt instruments that finance NBS, and creating insurance coverages for carbon credits generated by these solutions (UCSC and USACE, 2024).

Strong public-private partnerships (PPPs) and significant capacity building are essential. This involves enhancing the local community's ability to plan, implement, maintain, and insure NBS. Additionally, it is important to create professional development courses tailored for risk managers and insurance professionals, designed collaboratively with input from private industry modelers, public and private insurance providers, public risk management agencies, municipal leaders, and academics . Building strong working relationships between public risk managers and the private risk industry will further facilitate widespread adoption of NBS. Integrating nature into national, state, and community disaster mitigation and recovery plans also presents a crucial opportunity for financing. Innovative funding mechanisms, like Environmental Impact Bonds, should be explored as low-risk options for supporting NBS. Importantly, we need clear guidance on how to evaluate the adaptation benefits of NBS to encourage their broader implementation across various sectors (UCSC and USACE, 2024).

The success of NBS implementation relies on inclusive governance and collaborative production processes. This means working together with citizen stakeholders, researchers, and practitioners to design and implement NBS, often using positive visioning exercises to address potential equity issues (McPhearson et al., 2023)

Collaboration among scientific experts, municipalities, and other stakeholders is vital for developing and executing effective impact assessment plans. Implementing inclusive, transparent, and empowering governance processes is essential for achieving successful NBS outcomes, ensuring equitable participation, fair power-sharing, and clear recognition of rights and responsibilities (IUCN, 2020; McPhearson et al., 2023) . To overcome fragmented governance and ensure an equitable distribution of benefits, it's important to foster inter- and transdisciplinary collaboration that actively involves diverse stakeholders and knowledge systems (European Commission. Directorate General for Research and Innovation., 2021; McPhearson et al., 2023).

In conclusion, NBS provides a powerful and systemic approach to creating biodiverse, resilient, and inclusive urban environments. Their integration into risk management and the insurance sector represents not just a technical change, but a fundamental shift towards a nature-based urbanism that prioritizes both

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people and nature. By fostering integrated knowledge, enhancing collaboration across disciplines and sectors, and empowering communities, we can harness the full potential of NBS to build a more resilient, equitable, and sustainable future for everyone.

4.2.2 Early warning systems

EWS were formally defined in 2017 by UN Member States as comprehensive frameworks that integrate hazard monitoring, forecasting, risk assessment, and preparedness activities. These systems empower various stakeholders to take pre-emptive action against potential disasters (United Nations, 2016). Multi-hazard EWS are especially valuable as they can address multiple threats that may occur individually or in combination, enhancing warning efficiency through coordinated mechanisms.

As a cornerstone of disaster risk reduction, EWS fulfil several critical functions. They help prevent casualties, reduce injuries, and minimize economic losses from hazardous events. Their effectiveness relies heavily on community engagement, public awareness, efficient communication, and maintained readiness. These systems benefit a diverse range of stakeholders, including government officials and private businesses, by helping them prepare for climate-related emergencies while protecting their economic interests (Martínez et al., 2022).

The Sendai Framework (2015-2030) highlights the importance of EWS through its global target of increasing the availability of these systems by 2030 (UN, 2014). This framework advocates for a fundamental shift in the management and utilization of risk information, emphasizing the need for improved monitoring, assessment, and information sharing across institutions.

EWS significantly contribute to sustainable development goals, as recognized in the 2030 Agenda, particularly in areas such as food security, public health, urban resilience, and climate adaptation. The Paris Agreement specifically identifies EWS as crucial for enhancing adaptive capacity and reducing vulnerabilities to climate change.

Evidence shows that while the frequency of disasters has increased fivefold over the past 50 years due to climate change and extreme weather, mortality rates have decreased by two-thirds, largely because of improved warning systems. The 2019 Global Commission on Adaptation report revealed that EWS offer an exceptional return on investment—more than tenfold, the highest among adaptation measures (Figure 20). A mere 24 hours of advance warning can reduce disaster damage by 30% (Global Commission on Adaptation, 2016).

The Glasgow Climate Pact (COP26, 2021) emphasizes the need to scale up adaptation measures and urges

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developed nations to increase climate finance and technology transfer. While EWS require significant investment in infrastructure and maintenance, especially for meteorological and hydrological monitoring networks, their costs remain minimal compared to the potential losses they can prevent.

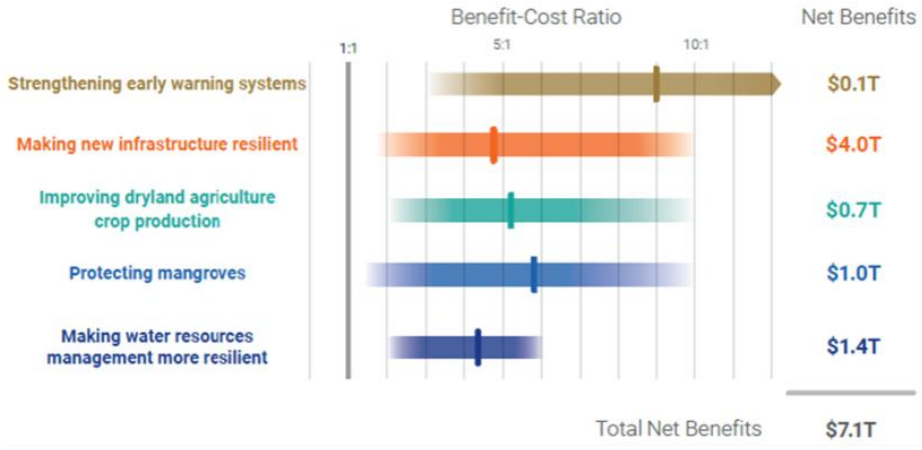

Figure 20. Benefits and cost of illustrative investments in adaptation (Global Commission on Adaptation, 2016)

The benefits of EWS are calculated based on the potential savings from damage reduction to assets after warning-prompted actions. The economic advantages primarily stem from the prevention of climate-related hazard damages, combining probability assessments of future events with vulnerability evaluations to determine potential economic savings through damage reduction. Determining damages combines a risk assessment in terms of the probability of future hazardous events to be averted, and a vulnerability assessment in terms of the damages that would be caused by those events and, therefore, the economic savings to be gained by their reduction (Martínez et al., 2022).

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5. Conclusions

The work presented provides a comprehensive overview of the landscape of climate risk assessment methodologies, highlighting significant advancement and gaps and challenges. The main conclusions presented are:

Best Practices:

- Risk assessment increasingly relies on the **IPCC's risk assessment framework**, which defines risk through the interaction of **hazard, exposure, and vulnerability**.
- A range of models are employed, including computationally intensive **catastrophe models**, empirical **actuarial models**, and qualitative **conceptual models**.

Key Gaps and Challenges:

- A primary limitation is the **scarcity and quality of reliable data**, especially for historical losses from high-impact, low-frequency events. There's also a notable absence of spatially explicit hazard values for individual events and rare availability of pluvial flood maps.
- Advanced models are **computationally demanding**, and their accuracy is sensitive to input data quality.
- **Inherent uncertainties** stem from model assumptions, data limitations, and expert judgment, restricting predictive capacity.
- Many insurers **over-rely on historical data** and generally **lack comprehensive integration of future climate change scenarios** (SSPs) and adaptation enhancement initiatives.
- There are strong limitations in **damage curve implementation** and institutional partnerships for their development within the Insurance sector.

Role of Climate Change:

- There is a critical need for **forward-looking risk assessments** that fully incorporate **SSPs** to project future climate and socioeconomic conditions.
- Advancements in **CMIP6 models** indicate that climate change impacts could be more severe than previously anticipated, emphasizing their importance for future risk assessments.

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Importance of Adaptation Measures:

- NBS are a **cost-effective, multi-beneficial interventions** that protect and restore ecosystems, thereby **reducing hazard, exposure, and vulnerability**, and strengthening resilience.
- EWS are highlighted as **highly effective in preventing casualties and minimizing economic losses**

And finally, an enhanced collaboration between public administrations and the insurance sector is essential. This includes significant improvements in data sharing (specially loses) and the development of more sophisticated modelling capabilities that incorporate future climate scenarios and socioeconomic factors. It is crucial to proactively adopt proven adaptation strategies, such as NBS and early EWS, to create robust, actionable, and transferable climate risk resilience.

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ANNEX: List of papers reviewed

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ID Article	File Name	Article Title	Authors (Year)	Risk Model Type	Hazard Type	Geographic Scope	Insurance Mechanism	Affected Agents	Key Notes
1	1-s2.0-S2468312420300092-main.pdf	Climate risk assessment for insurers: A multi-sector approach	Chen et al. (2020)	Multi-sector catastrophe model	Hurricane, flood, wildfire	China	Composite insurance	Insurers, government	Sectoral risk integration
2	s41598-020-63580-w.pdf	Global wildfire risk under climate change: modeling and mitigation	Zhang et al. (2020)	Global fire risk model	Wildfire	Global	ILS and parametric	Insurers, policymakers	Global risk hotspots identification
3	Hazardous simulations Pricing climate risk in US coastal insuran	Hazardous simulations: Pricing climate risk in US coastal insurance markets	Gray (2021)	Catastrophe model	Hurricane/coastal flood	USA (coastal)	Regulated private insurance	Regulators, insurers, homeowners	Integrates climate scenarios into pricing
4	J of Risk Insurance - 2023 - Li - Mitigating wildfire losses via insu	Mitigating wildfire losses via insurance-linked securities: Modeling and risk	Li et al. (2023)	Spatial-temporal actuarial model	Wildfire	USA (California)	ILS	Investors, homeowners	Enhances ILS pricing
5	1-s2.0-S2212420924001730-main.pdf	The role of microinsurance in climate adaptation	Kumar & Singh (2024)	Actuarial microinsurance model	Drought, flood	India	Microinsurance	Smallholder farmers	Assesses adaptation benefits
6	1-s2.0-S0264837723004362-main.pdf	Creating synergies between payments for ecosystem services and risk financing	Ranjan (2023)	Conceptual model	Flood, drought	India	Ecosystem-based insurance	Communities, insurers	Combines PES with risk transfer
7	s42979-022-01216-8.pdf	Modeling flood risk under climate change: A case study	Martinez et al. (2022)	Hydrological simulation model	Flood	Spain	Private flood insurance	Households, insurers	Case study modeling climate impact
8	A_systematic_literature_review_on_sustainability_i	A systematic literature review on sustainability issues along the value chain in insurance companies and pension funds	Barrera et al. (2023)	Systematic literature review on sustainability in insurance companies					
9	Risk Manage Insurance Review - 2022 - Steptoe - Advances in r	Advances in numerical weather prediction: Data science and open-source	Steptoe et al. (2022)	Software/data-science framework	Meteorological hazards	Global	Informational tools	Modelers, insurers	Open-source NWP tools
10	Softw Pract Exp - 2022 - Tao - Florida public hurricane loss mod	A Florida public hurricane loss model: Software system for insurance loss projec	Tao et al. (2022)	Numerical weather prediction integration	Hurricane	USA (Florida)	State-backed	Government, insurers, homeowners	Integrates NWP for projections
11	Disasters - 2015 - Joyette - Disaster risk insurance and catastro	Disaster risk insurance and catastrophe models in risk-prone small Caribbean is	Joyette & Salmon (2015)	Catastrophe model	Cyclones, flood	Caribbean islands	Parametric & public-private	Communities, governments	Recommends parametric triggers
12	Risk Manage Insurance Review - 2022 - Guo - Dynamic modelir	Dynamic modeling of public and private decision-making for hurricane risk	Guo et al. (2022)	Dynamic decision model	Hurricane	USA	Public-private partnerships	Governments, insurers	Policy vs private uptake interplay
13	hess-18-2305-2014.pdf	Hydrological extremes and insurance pricing under climate change	Smith et al. (2018)	Hydrological catastrophe model	Flood	Europe	Private flood insurance	Insurers, policyholders	Assess impacts of extreme rainfall
14	7_22.pdf	Integrating climate change into risk management	Garcia & Patel (2022)	Theoretical framework	Multi-hazard	Global	Guidelines for insurers	Insurers, regulators	Proposes integration framework
15	1-s2.0-S0013935117312756-main.pdf	Natural Assurance Scheme: A level playing field?	Denjean et al. (2017)	Theoretical framework	Multi-hazard	France	Mutual insurance scheme	Public authorities, citizens	Analyzes fairness in mutual schemes
16	1-s2.0-S0964569120300570-main.pdf	Parametric flood insurance: Lessons from pilot projects	Lee et al. (2020)	Actuarial model	Flood	Australia	Parametric insurance	Farmers, insurers	Evaluates pilot parametric schemes
17	s40797-022-00210-6.pdf	Parametric insurance for drought risk: Evaluation	O'Neil et al. (2022)	Parametric actuarial model	Drought	Africa (Sahel)	Parametric	Farmers, NGOs	Evaluates payout mechanisms
18	1-s2.0-S0167668712001345-main.pdf	Pricing and simulations of catastrophe bonds	Nowak (2012)	Catastrophe bond simulation	Earthquake, hurricane	Global	Catastrophe bonds (ILS type)	Investors, insurers	Simulates bond payouts under scenarios
19		Advances in risk assessment for climate change adaptation policy. In Philosoph and Engineering Sciences	Adger etal.(2018)						
20	Bibliografia D1.2 Advancements in actuarial risk modeling PIISA	A damage-based crop insurance system for flash flooding	Islam et al. (2022)	Parametric actuarial model	Flooding	Bangladesh	Demand model	Crop insurance	Satellite remote sensing approach
21		A GIS-based model for multiscale forest insurance analysis: The Italian case stu	Sacchelli et al. (2018)	Spatial-temporal actuarial model	Wildfire and storm	Italy	Pricing (supply model)	Forestry sector	Multi-hazard approach, GIS-based spatial analysis
22		A Public–Private Insurance Model for Disaster Risk Management: An Applicatio	Perazzini et al. (2022)	Multi-sector catastrophe model	Earthquakes, flooding	Italy	Partial equilibrium	Households	Single- and multi-hazard policy comparison
23		An actuarial model of forest insurance against multiple natural hazards in fir sta	Brunette et al. (2015)	Actuarial model	Wildfire, windstorm, insect (	Slovakia	Pricing (supply model)	Forestry sector	Multi-hazard approach
24		An agent-based model for evaluating reforms of the National Flood Insurance P	de Ruig et al. (2023)	Hydrological catastrophe model	Flooding	USA	Agent-based	Households	NFIP reform evaluation
25		An Agent-Based Model of Flood Risk and Insurance	Dubbelboer et al. (2017)	Hydrological catastrophe model	Flooding	UK	Agent-based	Households	FloodRe scheme analysis
26		Application of insurance modelling tools to climate change adaptation decision-r	Walker et al. (2016)	Catastrophe model	Cyclones	Australia	Pricing (supply model)	Constructed assets	Climate change adaptation, stochastic approach
27		Assessing surface water flood risk and management strategies under future clin	Jenkins et al. (2017)	Hydrological catastrophe model	Flooding	UK (London, Camden)	Agent-based	Households	Climate change scenarios, FloodRe analysis
28		Charity hazard and the flood insurance protection gap: An EU scale assessmen	Tesselaar et al. (2022)	Multi-sector catastrophe model	Flooding	European Union + UK	Partial equilibrium	Households	Four market structures, charity hazard analysis
29		Climate change impacts on pricing long-term flood insurance: A comprehensive	Aerts & Botzen (2011)	Hydrological catastrophe model	Flooding	Netherlands	Pricing (supply model)	Households	Forward-looking model with climate change scenarios
30		Development and application of a probabilistic method for wildfire suppression c	Thompson et al. (2015)	Global fire risk model	Wildfires	USA	Pricing (supply model)	Wildfire suppression costs	Suppression cost modeling comparable to premiums
31		Evaluation Model for Risk Insurance Premiums of Building Damage Caused by	Sidi et al. (2017)	Actuarial model	Flooding	Indonesia	Pricing (supply model)	Buildings	Premium as random variable using multiple methods
32		Flood Catastrophe Model for Designing Optimal Flood Insurance Program	Ermolieva et al. (2017)	Hydrological catastrophe model	Flooding	Netherlands	Partial equilibrium	Households and firms	Quantile-based optimization
33		Flood insurance arrangements in the European Union for future flood risk	Hudson et al. (2019)	Multi-sector catastrophe model	Flooding	European Union	Partial equilibrium	Households	Comparative analysis of insurance systems
34		Forest property insurance: an application to Portuguese woodlands	Pinheiro & Ribeiro (2013)	Actuarial model	Wildfire	Portugal	Pricing (supply model)	Forestry sector	Expected annual burned area approach
35		Future Public Sector Flood Risk and Risk Sharing Arrangements: An Assessme	Unterberger et al. (2019)	Multi-sector catastrophe model	Flooding	Austria	Partial equilibrium	Public infrastructure	Three insurance market forms, government focus
36		Game theoretic approach for flood risk management considering a financial mo	Moosakhaani et al. (2022)	Financial simulation model	Flooding	Iran	Game theory	Households and government	Three insurers with dual insurance plans
37		How the USA can benefit from risk-based premiums combined with flood protec	de Ruig et al. (2022)	Hydrological catastrophe model	Flooding	USA	Agent-based	Households	Risk-based premiums with adaptation measures
38		Impacts of climate change and remote natural catastrophes on EU flood insurar	Tesselaar et al. (2020a)	Multi-sector catastrophe model	Flooding	European Union + UK	Partial equilibrium	Households	Soft vs hard reinsurance markets analysis
39		Incentivising flood risk adaptation through risk based insurance premiums	Hudson et al. (2016)	Hydrological catastrophe model	Flooding	France and Germany	Partial equilibrium	Households	Adaptation incentives through pricing
40		Insurance and Forest Rotation Decisions Under Storm Risk	Loisel et al. (2020)	Dynamic decision model	Storm	France	Partial equilibrium/Game theory	Forestry sector	Forest rotation decisions, age-dependent vulnerability
41		Insurance Premium Determination Model and Innovation for Economic Recover	Kalfin et al. (2022)	Multi-sector catastrophe model	Natural disasters	Indonesia	Pricing (supply model)	Households	Single-hazard and multi-hazard approach
42		Insurance Pricing for Windstorm-Susceptible Developments: Bootstrapping App	El-Adaway (2012)	Actuarial model	Windstorms	USA	Pricing (supply model)	Civil infrastructure	Bootstrapping approach
43		Insuring future climate catastrophes	Kunreuther et al. (2013)	Catastrophe model	Hurricane	United States (Florida)	Pricing (supply model)	Households	Hard vs soft insurance market conditions
44		Is forest insurance a relevant vector to induce adaptation efforts to climate chan	Brunette et al. (2017)	Theoretical framework	Forest damage (general)	Global	Partial equilibrium	Forestry sector	Adaptation incentives focus
45		Modeling Insurer-Homeowner Interactions in Managing Natural Disaster Risk	Kesete et al. (2014)	Dynamic decision model	Hurricane	United States (North Carol	Game theory	Households	Stackelberg game approach
46		Modeling the integrated roles of insurance and retrofit in managing natural disas	Peng et al. (2014)	Dynamic decision model	Hurricane	USA	Game theory	Households	Multi-stakeholder approach, retrofit integration
47		Novel framework for assessing long-term flood risk management pathways	Tanaka et al. (2022)	Hydrological simulation model	Flooding	Japan	Agent-based	Households	Climate change scenarios, no explicit insurer modeling
48		On insurance as a tool for securing forest restoration after wildfires	Barreal et al. (2014)	Actuarial model	Wildfire	Spain	Partial equilibrium	Forestry sector	Adaptation measures included
49		Pricing Flood Insurance with a Hierarchical Physics-Based Model	Boudreault et al. (2020)	Hydrological simulation model	Flooding	Canada	Pricing (supply model)	Households	High spatial resolution, household-level premiums
50		Regional inequalities in flood insurance affordability and uptake under climate cl	Tesselaar et al. (2020b)	Multi-sector catastrophe model	Flooding	European Union + UK	Partial equilibrium	Households	Multiple scenarios, affordability focus
51		Risk-layering and optimal insurance uptake under ambiguity: With an applicatio	Birghila et al. (2022)	Parametric actuarial model	Drought	Austria	Demand model	Farmers	Ambiguity and risk layering focus
52		Strengthening insurance partnerships in the face of climate change – Insights fr	Crick et al. (2018)	Hydrological catastrophe model	Flooding	UK	Agent-based	Households	FloodRe scheme analysis
53	Bibliografia D1.3: Design and Modelling Framework for WP3 Pilots	A comparison of hypothetical risk attitude elicitation instruments for explaining f	Menapace et al. (2016)	Actuarial microinsurance model	Agricultural risks	Italy	Demand model	Farmers	Risk attitude measurement
54		Assessing the demand for hydrological drought insurance in irrigated agricultur	Gómez-Limón & Granado-	Parametric actuarial model	Drought	Spain	Demand model	Farmers	Hydrological drought insurance demand
55		Government-sponsored natural disaster insurance pools: A view from down-unc	McAneney et al. (2016)	Multi-sector catastrophe model	Natural disasters (general)	Australia	Partial equilibrium	Households	Government-sponsored insurance pools
56		HAZUS-MH hurricane model methodology	Vickery et al. (2006)	Catastrophe model	Hurricanes	General (methodology)	N/A (Hazard modeling)	N/A	Hurricane hazard modeling methodology
57		How insurance can support climate resilience	Surminski et al. (2016)	Theoretical framework	Climate risks	General	Policy framework	Various	Insurance role in climate resilience building
58		Influence of flood risk characteristics on flood insurance demand	Seifert et al. (2013)	Theoretical framework	Flooding (riverine)	Germany and Netherlands	Demand model	Households	Comparative demand analysis
59		Insights into Flood Risk Misperceptions of Homeowners in the Dutch River Delta	Mol et al. (2020)	Theoretical framework	Flooding (riverine)	Netherlands	Demand model	Households	Risk perception analysis
60		LAI estimation through remotely sensed NDVI following hail defoliation in maize	Furlanetto et al. (2023)	Software/data-science framework	Hail	Italy	N/A (Impact assessment)	Agricultural crops	Remote sensing for hail damage assessment
61		Supplement to A Statistical Deterministic Approach to Hurricane Risk Assessme	Emanuel et al. (2006)	Catastrophe model	Hurricanes	General (methodology)	N/A (Hazard modeling)	N/A	Statistical-deterministic hurricane modeling
62		The demand for public–private crop insurance and government disaster relief	Liesivaara & Myyrä (2017)	Actuarial microinsurance model	Agricultural risks	Finland	Demand model	Farmers	Public-private insurance interaction
63		The Role of Insurance in Reducing Direct Risk—The Case of Flood Insurance	Surminski (2014)	Theoretical framework	Flooding	General	Conceptual analysis	Various	Role of insurance in risk reduction